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AIRWORTHINESS CONSIDERATIONS FOR STOL AIRCRAFT

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16. Abstract

Criteria are presented for satisfactory performance and handling qualities of powered-lift STOL transport aircraft in commercial operation. These criteria were formulated from information gathered during NASA flight tests of STOL aircraft. The main emphasis is placed on the landing-approach mode because this regime has caused the greatest difficulty and is the most demanding portion of the flight.

It was concluded that STOL aircraft utilizing power to develop lift can safely approach and land with smaller speed margins than conventional aircraft. No single factor that would relate a demonstrated performance to field length could be developed because data were insufficient for assessing consistency of performance.

Mechanical control characteristics are more important in overall handling than they are for conventional aircraft because the stability and damping are generally low at STOL speeds. High levels of aerodynamic stability and damping are not necessarily desired because they allow the aircraft to be more easily disturbed in gusty air.

Additional research is necessary for determining more accurately the effect of gusts, shears, and crosswinds on performance and handling qualities.

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SUMMARY

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It was concluded that STOL aircraft utilizing power to develop lift can safely approach and land with smaller speed margins than conventional aircraft. No single field length factor that would relate a demonstrated performance to an operational field length could be developed because insufficient data were available.

Mechanical control characteristics are more important in overall handling than they are for conventional aircraft because the stability and damping are generally low at STOL speeds. High levels of aerodynamic stability and damping are not necessarily desired because they allow the aircraft to be more easily disturbed in gusty air.

Additional research is necessary for determining more accurately the effect of gusts, shears, and crosswinds on performance and handling qualities.

INTRODUCTION

There is increased interest in short take-off and landing (STOL) aircraft by airlines and government agencies for commercial air travel (refs. 1 and 2). The low-speed characteristics of STOL aircraft should provide added convenience to the air traveler because such craft can be flown into small airfields and restricted space thereby expanding air travel to a larger portion of the population. In addition, STOL aircraft show promise in alleviating some of the congestion in and about our major air terminals by being able to operate in currently unused portions of the airspace and airports.

At present, STOL capability cannot be exploited in a commercial short haul system. When STOL performance is achieved by reduced wing loading and increased power loading, the aircraft has a low cruise speed, is quite disturbed by gusty conditions, and contains considerable design and performance compromises to achieve safety. When STOL performance is obtained by including a significant portion of the lift and control from the propulsion system (hereafter referred to as powered lift), higher wing loadings can be utilized. Such STOL aircraft are of interest to the major airlines because they have good cruise characteristics, are less disturbed in gusty conditions, and have improved passenger comfort. However, current airworthiness standards do not permit exploiting the low-speed potential of powered-lift aircraft.

Before powered-lift STOL aircraft can be utilized commercially, several questions must be answered. First and foremost is, what will be required in terms of low-speed performance and safety margins? Second, how steep an approach and climbout angle can these aircraft routinely fly, and how large a runway will be needed for all surface and atmospheric conditions anticipated in daily operation? Third, what handling qualities must these aircraft have to allow the pilot to fly small, steep patterns in a safe and easy manner under instrument as well as visual flight conditions.

The study that follows was made to provide guidelines and criteria for answering the questions on performance margins and handling qualities required for powered-lift STOL aircraft. Previously published NASA reports on V/STOL and STOL aircraft were reviewed; these reports describe tests made primarily to understand the capabilities and limitations of these aircraft and to examine specific problem areas that occurred. The reported results could not be directly used to answer the previous questions because the results were either too limited or not addressed to aspects of commercial STOL and V/STOL aircraft. Recently, the FAA published "Tentative Airworthiness Standards for Verticraft/Powered Lift Transport Category Aircraft" (ref. 3). This publication provided some guidelines, but did not answer all of the previous questions. Therefore data were extracted from previous NASA reports, re-examined in light of more recent knowledge, and re-addressed to a commercial environment so that guidelines and criteria could be developed. Data were primarily extracted from tests with which the authors had close familiarity so that the available information could be more consistently examined. Greatest emphasis was placed on information obtained in the STOL regime by STOL aircraft that had the most promising operational characteristics. It was assumed that the vehicles of interest will be flying in the 40 to 80 knot speed regime with descent and ascent angles of at least 6°, and will require a high degree of maneuverability to operate in restricted airspace.

Guidelines are developed for safe, low-speed operation with emphasis on consistent performance over a wide variety of environmental and runway conditions. Where possible, criteria for safe low-speed handling are presented in a form that can be easily measured and interpreted by the pilot. Data that substantiate these criteria are also presented. In this report primary emphasis is on characteristics in the landing mode where it has been found most difficult to achieve satisfactory performance, handling qualities, and operational characteristics. Further, this is a critical area of the flight envelope because of the number of decisions and the judgment that must be made in the brief period of time before touchdown.

The information and criteria presented should assist the designer in performing trade-off studies in the preliminary design phase. It should also give the potential operator and regulatory agencies a better idea of how the pilot may operate the STOL aircraft, and what he requires in terms of performance margins and handling qualities. While the information was developed primarily for STOL aircraft, it should be equally applicable to VTOL aircraft operating in the STOL mode. The information and criteria presented are by no means complete or intended to be conclusive. Areas requiring further research are noted, and it is expected that the criteria will be revised and expanded as more experience is gained and new unique vehicles are tested.

NOTATION

a_n	incremental acceleration normal to flight path, ft/sec^2
a_x	longitudinal acceleration along flight path, $\frac{dV}{dt}$, ft/sec^2
A_x	longitudinal acceleration as measured by an accelerometer at the center of gravity, g
A_z	normal acceleration as measured by an accelerometer at the center of gravity, g
BLC	boundary-layer control
$\bar{c}$	mean aerodynamic chord, ft
C_D	drag coefficient, including propulsive thrust
C_L	lift coefficient, including propulsive thrust
$C_{L_{1g}}$	lift coefficient in steady-state flight
F_{L_p}	lateral control force, lb
g	acceleration of gravity, ft/sec^2
h	height above runway, ft
IFR	Instrument Flight Rules
I_{xx}, I_{yy}, I_{zz}	moments of inertia, slug ft^2
L_p	damping in roll, $\frac{\partial L/I_{xx}}{\partial p}$, 1/sec
L_r	roll due to yaw rate, $\frac{\partial L/I_{yy}}{\partial r}$, 1/sec

L_β dihedral effect, $\frac{\partial L/I_{xx}}{\partial \beta}$, $1/sec^2$

L_{δ_L} rolling acceleration for full lateral control surface deflection, $\frac{L}{I_{xx}}$, rad/sec^2

$L_{\delta_{L_p}}$ rolling acceleration per inch lateral control deflection, $\frac{\partial L/I_{xx}}{\partial \delta_{L_p}}$, $rad/sec^2/in.$

M_q damping in pitch, $\frac{\partial M/I_{yy}}{\partial q}$, 1/sec

M_V speed stability, $\frac{\partial M/I_{yy}}{\partial V}$, $1/sec^2/ft/sec$

M_α angle-of-attack stability, $\frac{\partial M/I_{yy}}{\partial \alpha}$, $1/sec^2$

N_p yaw due to roll rate, $\frac{\partial N/I_{zz}}{\partial p}$, 1/sec

N_r directional damping, $\frac{\partial N/I_{zz}}{\partial r}$, 1/sec

N_β directional stability, $\frac{\partial N/I_{zz}}{\partial \beta}$, $1/sec^2$

$N_{\dot{\beta}}$ damping due to rate of sideslip, $\frac{\partial N/I_{zz}}{\partial (d\beta/dt)}$, 1/sec

N_{δ_L} adverse yaw due to full lateral control, $\frac{N}{I_{zz}}$, rad/sec^2

p roll angular velocity (right roll, positive), rad/sec

PR pilot rating

q pitch angular velocity (nose up, positive), rad/sec

q_∞ free-stream dynamic pressure, lb/ft^2

r yaw angular velocity (nose right, positive), rad/sec

$\frac{R}{C}$ rate of climb, ft/min

S wing area, ft^2

SHP shaft horsepower

t	time, sec
t_a	ramp time for control input, sec
t_{30}	time to reach 30° bank angle, sec
T	transparency, average inboard propeller blade angle minus average outboard propeller blade angle, deg
T_c'	thrust coefficient, $\frac{\text{thrust}}{q_\infty S}$
$T_{1/2}$	time to damp one-half amplitude, sec
T_2	time to double amplitude, sec
V	true airspeed, knots or ft/sec
V_a	approach airspeed, knots
V_C	calibrated airspeed (at low Mach number $V_C = V\sqrt{\sigma}$), knots
V_{FE}	maximum flaps-extended speed, knots
V_{min}	minimum airspeed in steady-state flight at reference power condition, knots
V_{MC}	minimum control airspeed, knots
V_R	airspeed at which aircraft is rotated, knots
V_{XW}	crosswind component, knots
V_1	critical decision speed, knots
V_2	optimum climb speed, knots
W	gross weight, lb
α	angle of attack, deg
α_u	indicated or uncorrected angle of attack, deg
β	angle of sideslip, deg
γ	flight-path angle (above horizon, positive), deg
δ_a	aileron deflection, deg
δ_f	flap deflection, deg
δ_L	lateral control surface position, deg

δ_{L_p} lateral control position (positive movement producing positive moment; right, positive or clockwise positive), in., or deg

δ_{M_p} longitudinal control position (positive direction producing positive moment; aftstick is positive), in.

δ_{N_p} rudder pedal position (positive direction producing positive moment; right pedal forward, positive), in.

δ_r rudder deflection (trailing edge left, positive), deg

θ pitch attitude (nose up, positive), deg

$\ddot{\theta}_0$ pitch angular acceleration when pitch rate is zero, rad/sec^2

ξ damping ratio

ρ air density, slugs/ft^3

σ density ratio

τ time to 67 percent of steady-state value, sec

ϕ bank angle (right wing down, positive), deg

ϕ_1 bank angle after 1 sec, deg

$\ddot{\phi}$ roll angular acceleration, rad/sec^2

$\ddot{\phi}_0$ roll angular acceleration when roll rate is zero, L_{δ_L}, rad/sec^2

ψ heading angle, deg

$\ddot{\psi}_0$ yaw angular acceleration when yaw rate and sideslip angle are zero, rad/sec^2

ω frequency, rad/sec

ω_d directional frequency, rad/sec

DESCRIPTION OF VEHICLES

The first figure illustrates the variety of aircraft that were tested and evaluated by NASA and that formed the basis of this report. The first NASA STOL flights were made in the Stroukoff YC-134A in 1959 (ref. 4). Since that time, the remaining STOL aircraft have been evaluated (refs. 5 to 15). The aircraft have encompassed gross weights from under 3,000 lb to over 150,000 lb and wing loadings from 23 to over 56 lb/sq ft. Approach speeds have ranged from 40 to 90 knots. The geometric characteristics of these aircraft are

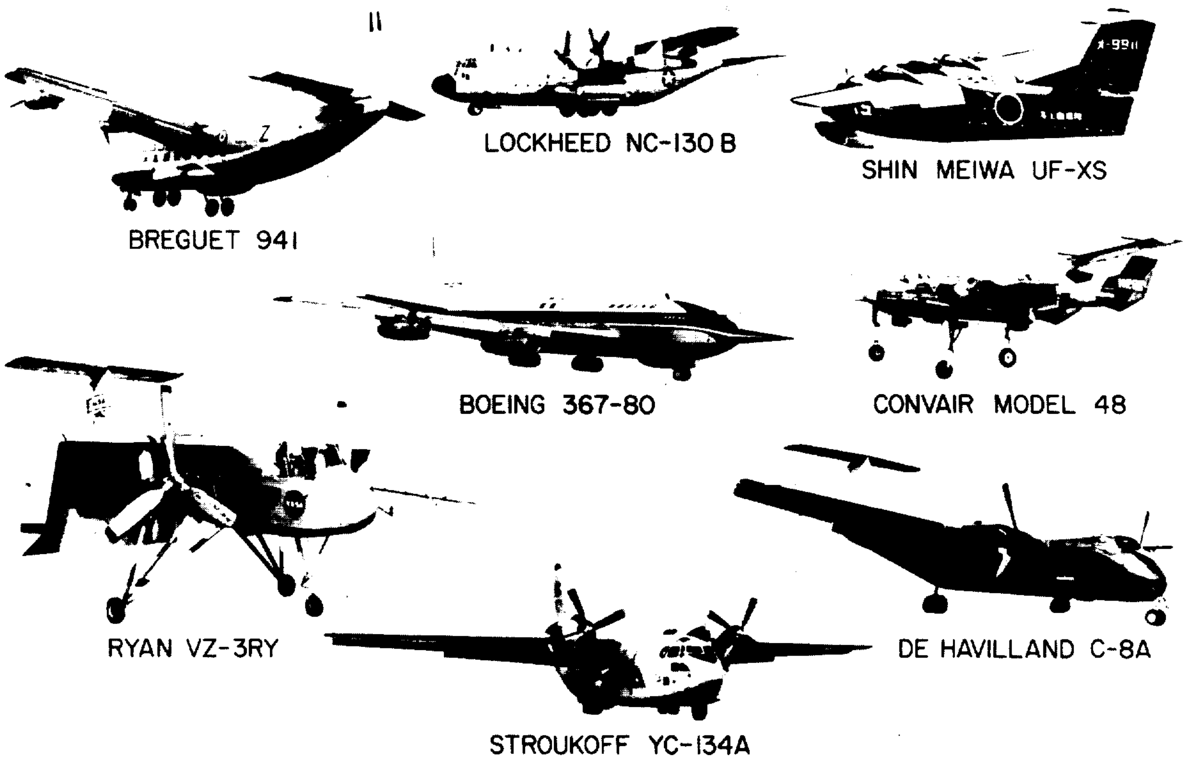


Figure 1.- STOL aircraft used for this report.

summarized in table I. The majority of these aircraft were powered by turbo-propeller engines, although two were powered by reciprocating engines. One jet aircraft, although perhaps not STOL in the sense of requiring only a short field length, is included because it had some degree of powered lift by virtue of boundary layer control and engine exhaust impinging on the flap, and its variable stability system had been used to help develop some of the handling qualities criteria that will be discussed later. Although these aircraft were used to formulate the criteria that will be presented, it should not be implied that they were all suitable for commercial STOL operation.

DISCUSSION OF LOW SPEED ENVELOPE

Illustration of STOL or Powered-Lift Envelope

The lift capabilities of STOL aircraft are as much a function of thrust as they are of angle of attack; thrust not only reduces the minimum airspeed but can also control the vertical acceleration. For these reasons, safe operating speeds cannot be related to a singular stall speed, but must be related to thrust or power utilized. A method of relating these parameters with an operational envelope is developed in the following sections.

Lift-drag polars.- Curves of lift and drag coefficients at different thrust coefficients for an illustrative STOL aircraft in a landing configuration (Breguet 941, ref. 10) are presented in figure 2. Since the curves include the thrust component, $C_D = 0$ corresponds to level unaccelerated flight. The following approximate relations are useful for later analysis:

$$\frac{a_n}{g} = \frac{C_L}{C_{L_{1g}}} - 1 = \frac{\Delta C_L}{C_{L_{1g}}} \qquad (1)$$

$$\gamma + \frac{a_x}{g} = - \frac{C_D}{C_{L_{1g}}} \qquad (2)$$

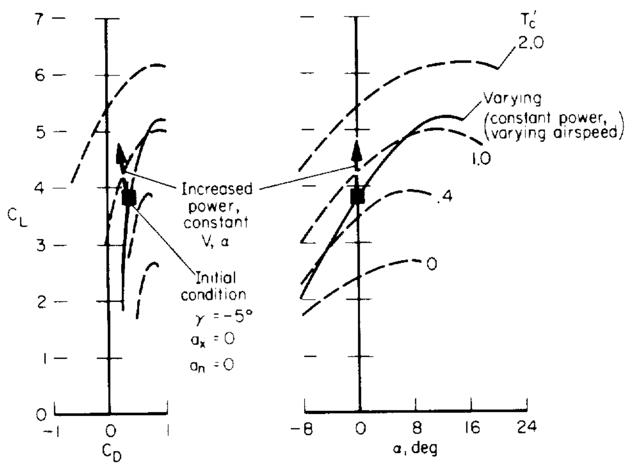


Figure 2.- Lift-drag curves in landing configuration (ref. 10, $\delta_f = 98°$).

The solid curve represents the lift and drag characteristics measured as angle of attack is slowly increased and airspeed decreased at a constant power or throttle setting; the thrust coefficient increases at constant power as the airspeed is reduced because thrust is nearly constant as dynamic pressure is reduced ($T_c' = \text{thrust}/(1/2)\rho V^2 S$). These characteristics represent steady-state flight conditions. The dotted curves are for constant thrust coefficients which correspond to values measured in accelerated flight when angle of attack is changed at constant airspeed. The change in lift and drag obtained by modulating power at constant angle of attack and airspeed is depicted by the dashed line starting at $C_L = 3.9$ and $\alpha = 0°$. The corresponding vector is inclined over 75° and represents the angle through which the effective thrust (propeller slipstream) was vectored by the large flaps deflected to 98°; consequently, large increases in lift can be obtained by increasing the thrust level. In contrast, a conventional aircraft has little deflection of the propulsive force and the lift curves with power on are near the power-off curves.

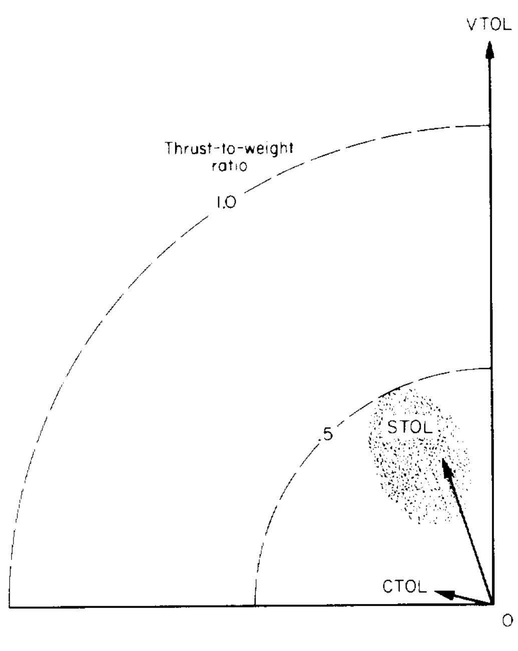


Figure 3.- Resultant thrust vector in landing configuration.

Vector diagram.- Figure 3 compares the STOL thrust vector from figure 2 with those for a VTOL and conventional aircraft. This diagram is useful in further illustrating the definition of STOL and explaining some of the implications of "powered lift." The diagram refers primarily to the landing portion of the flight envelope, which is the most critical area in terms of attaining good descent capability with adequate control and handling qualities. In the approach conventional aircraft primarily require thrust to balance the drag, and the thrust level is only a fraction of the gross weight. Modulation of thrust produces primarily the horizontal acceleration while rotation produces normal acceleration. In contrast, the VTOL requires thrust in excess of its weight, and modulation of thrust produces primarily normal acceleration; horizontal acceleration is obtained by rotating the thrust vector or aircraft attitude. The STOL aircraft lies between these two and the thrust level required is a significant fraction, but still much less than the weight. For the STOL example, modulating thrust produces more normal acceleration than horizontal acceleration, and rotation of the aircraft produces less normal acceleration than does rotation of conventional airplanes. As a consequence, corrections to the flight path during the approach are most expeditiously accomplished by modulation of the thrust, while attitude or angle of attack is maintained relatively constant.

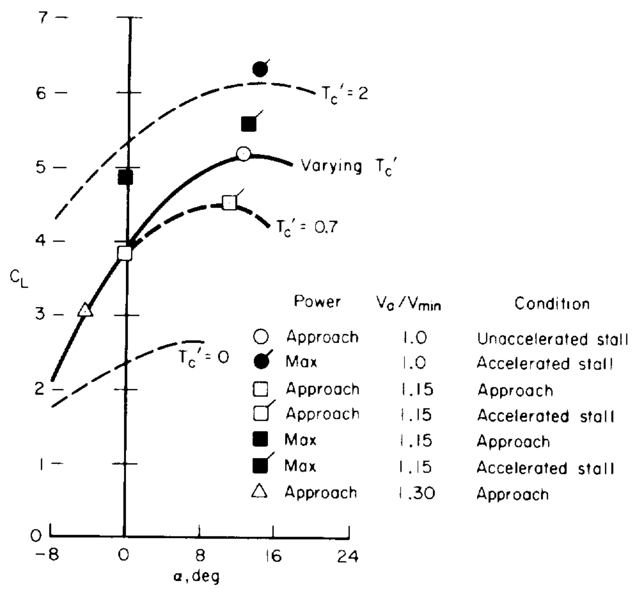


Figure 4.- Lift curves for accelerated and unaccelerated flight, landing configuration (ref. 10, δ_f = 98°).

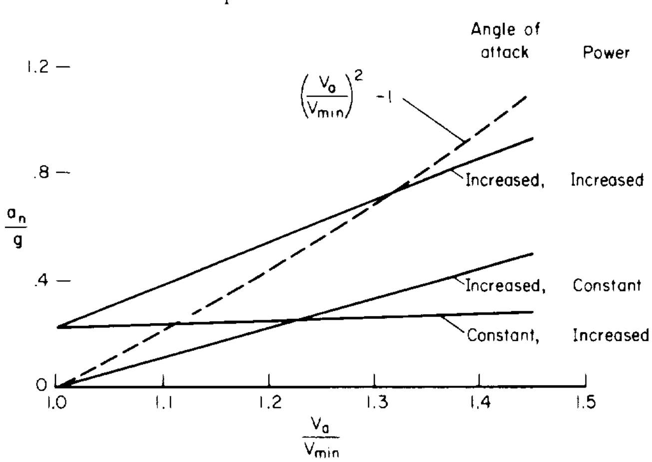


Figure 5.- Calculated normal acceleration capability for different approach speeds.

Normal acceleration capability.- It is important to examine the magnitude of normal acceleration available from changes in power and angle of attack to assess the maneuvering capability of STOL aircraft and to determine a safe operating speed. Figures 4 and 5 were prepared to illustrate the relationship between power, lift coefficient, ratio of approach speed to minimum speed, and normal acceleration. These figures were based on the lift characteristics presented in figure 2. The maximum power condition is for one of the four gas generators inoperative with all four propellers operating by virtue of the interconnecting shafts used in the aircraft (Breguet 941, ref. 10).

The solid curve of figure 4 represents lift coefficients measured under steady-state flight conditions at a constant approach-power setting. The resulting maximum lift coefficient was 5.2. If the approach speed is chosen at 15 percent above the minimum speed ($V_a/V_{min} = 1.15$), the lift coefficient can be increased from 3.9 to only 4.5 by an accelerated stall at constant power. However, if power is applied at the approach angle of attack, the lift coefficient can be increased to 4.9; if power and angle of attack are increased the lift coefficient is increased from 3.9 to 5.6. The corresponding incremental normal-acceleration capabilities are summarized in figure 5. For reference purposes, the acceleration capability of a conventional aircraft defined by $(V_a/V_{min})^2 - 1$ is also included.

The normal acceleration obtained with a STOL aircraft by changing angle of attack only, is less than that of a conventional aircraft at the same ratio of approach to minimum speed. However, this deficiency is compensated by the normal acceleration that can be provided by the propulsion system even near the minimum speed of the aircraft. Relations like those shown in figure 5 were also obtained with the other STOL aircraft tested; in each case, the portion of acceleration obtained from the propulsion system was dependent on the extent of thrust vectoring and the power available.

Although the previous characteristics were for wings level flight, the same principles apply for banked-turning flight. When maneuvering a STOL aircraft by banking, the pilot uses power to maintain the desired altitude or rate of descent at the approach angle of attack, and, therefore, the stall margin is not decreased in turning flight. For example, a 30° banked turn at $V_a/V_{min} = 1.15$ would require an increase in lift coefficient from 3.9 to 4.5 which would be obtained by applying power and maintaining the approach angle of attack. In this condition, the angle of attack and stall margins are unchanged and an incremental normal acceleration of over 0.15 could still be obtained by rotation. In contrast, the airspeed of a conventional aircraft must be increased in turning flight if the stall margin is to remain constant.

Operational envelope.- Since the stall or minimum speed attainable varies considerably with power, it is necessary to examine the aircraft's capability in terms of parameters that interrelate lift, drag, and thrust (or power). This can be done by means of an operating envelope for steady state flight. Such an envelope was developed from the basic curves of figure 2 and is presented as figure 6. On the left, the envelope is given in terms of flight-path angle versus airspeed, which is useful in analyzing the aircraft's performance (obstacle clearance, landing distance, etc.). However, the pilot does not normally have a flight-path indicator, and an alternate presentation in terms of rate of climb versus airspeed is shown in the right-hand figure.

Minimum speed, V_{min}.- The minimum speed line of figure 6 represents the lowest speed to which the aircraft is controllable in steady flight with each thrust level. The minimum speed in some aircraft may be coincident with a conventional stall, but in others it may be established by a control limit, or the onset of objectionable buffeting, undesirable pitching or rolling moments, or a rapid increase in sink rate. One particular aircraft, which had its wing immersed in the slipstream of opposite rotation propellers, exhibited no noticeable behavior other than airspeed and sink rate slowly increasing, indicating that the aircraft had exceeded its maximum lift capabilities.

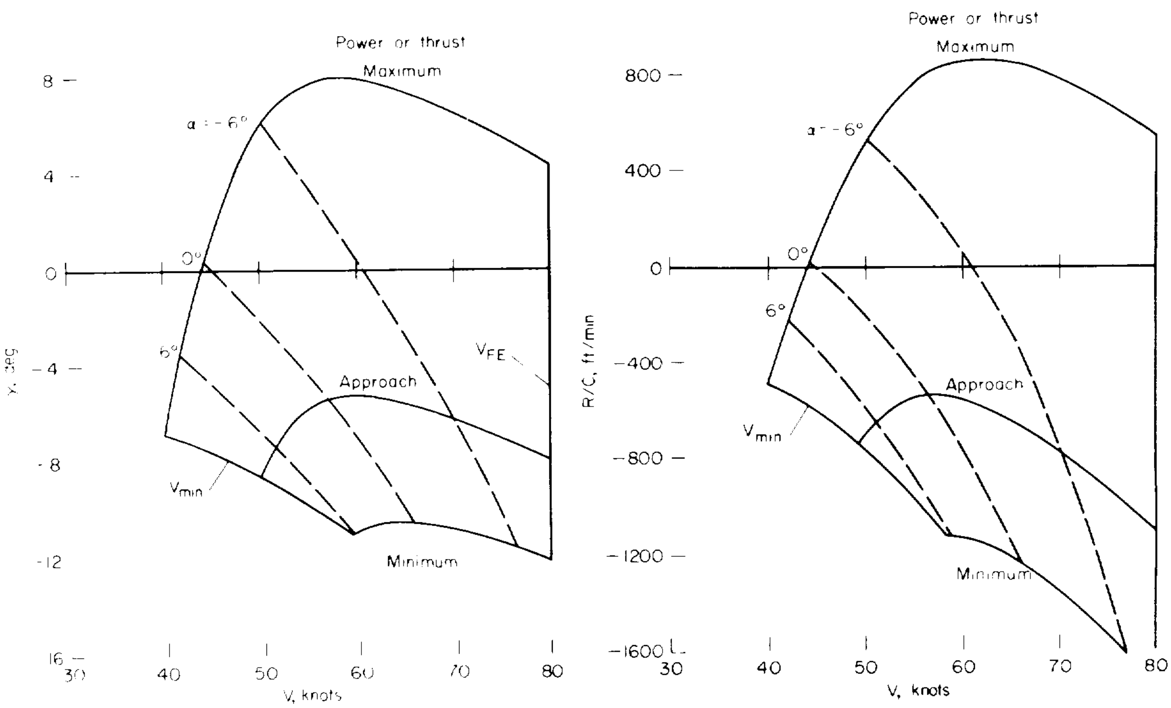


Figure 6.- Operational envelope for landing configuration (ref. 10, δ_f = 98°) steady-state flight.

Climb and descent capability.- The upper and lower boundaries of the envelope in figure 6 are established, respectively, as the climb capability with maximum available thrust applied, and the maximum descent capability with flight idle thrust. The envelope is bounded on the right side by the structural limit imposed on the configuration; in this case, the maximum flaps-extended speed, V_{FE}.

Included on the figure are lines of constant power or thrust and lines of constant angle of attack. The local slope of the constant thrust lines indicate whether the aircraft is on the front or back side of the drag-velocity curve. Operating STOL aircraft on the back side of the drag-velocity curve has not posed the problem that has occurred with conventional aircraft where thrust cannot be used to rapidly develop normal acceleration.

Restrictions Imposed on the Operational Envelope for Safety

The operational envelope developed in the earlier section represents the aerodynamic capability of the aircraft if one does not consider powerplant failures, safety margins, performance, or handling qualities. Safety margins must be imposed on this operating envelope to establish safe approach, landing, and take-off speeds. In the initial portion of the following discussion, it will be assumed that the propulsion system is interconnected to maintain symmetry and that the handling qualities are acceptable. Later, the effects of asymmetry will be discussed.

Propulsion system failure.- Reference 3 pointed out that safe operation with the most critical power-plant system inoperative will continue to be required for commercial transports utilizing powered lift. When a propulsion system failure causes no asymmetry (e.g., cross-ducted or cross-shafted) and no change in the minimum speed boundary, the only restriction to the envelope is a decrease in the available climb gradient. This effect is shown in figure 7 for the aircraft of reference 10. To utilize this envelope with such aircraft, the propeller control system must be highly reliable and be safeguarded so that malfunctions have relatively minor effects on controllability of the aircraft.

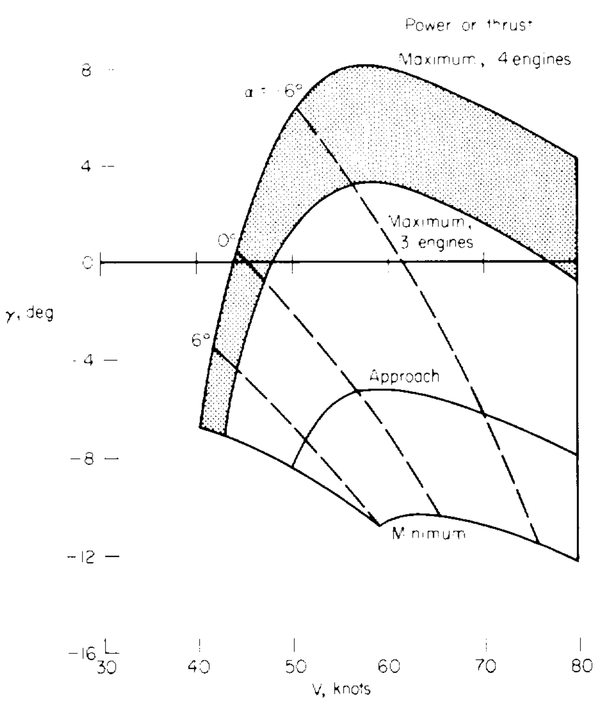


Figure 7.- Loss of engine; symmetry maintained.

Minimum speed margin.- The most important restriction to the operating envelope is the margin that must be maintained from the minimum speed line. This margin is required for one or more of three reasons: First, to provide a range of airspeeds or angles of attack that would allow the pilot to maintain adequate control of the aircraft when wind shears are encountered or when he inadvertently allows the approach reference parameter to deviate from the desired value; second, to provide protection from gusts which might momentarily increase the angle of attack or decrease the airspeed; and, third, to provide a maneuvering and flare capability. Table II presents the margins required by the various aircraft tested and indicates the reasons for selecting these margins. Generally, a 15-percent margin above the minimum airspeed was selected when sufficient normal acceleration was available for the landing flare. The effect of this margin on the envelope is shown in figure 8.

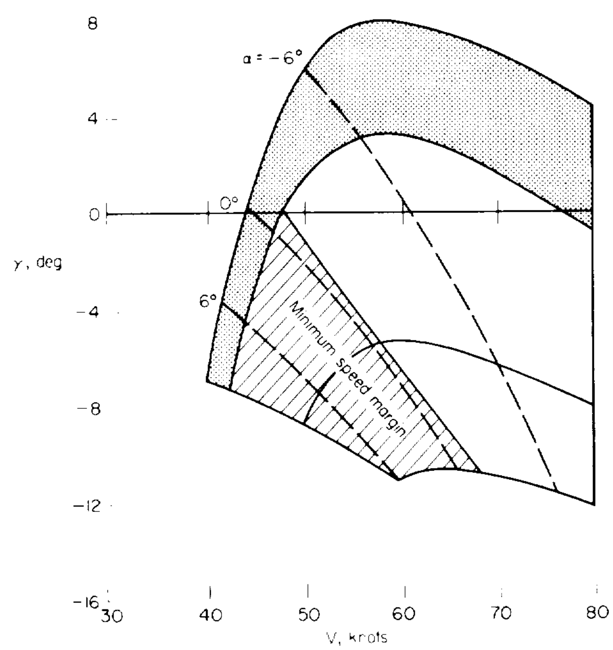


Figure 8.- Minimum speed margin.

The 15-percent margin was sufficient to account for inadvertent speed excursions, wind shears, and gusts encountered during the tests, and also to permit maneuvering other than complete flaring of the aircraft. It was not possible to evaluate each of those requirements separately; therefore, the margin is presented as a singular value. For the example aircraft used in figure 8, the 15-percent margin resulted in an approach speed of 60 knots at a 6° descent angle. It was calculated that this margin permitted any of the following: (1) a vertical gust of 10 knots without buffeting, and larger magnitudes without exceeding maximum lift and control limits; (2) an instantaneous 7-1/2 knot horizontal airspeed reduction with an altitude loss of less than 30 feet when power was applied 2 seconds after initial vertical acceleration; (3) an incremental normal acceleration of more than 0.2 g when power was applied throughout the angle-of-attack range including the stall; (4) an incremental normal acceleration of 0.15 g when angle of attack was increased rapidly; (5) a steady 30° banked turn with the capability of developing an additional 0.15 g by increasing angle of attack. Although the STOL flight tests included flying in some turbulence and winds, it is possible that more severe environmental conditions might be encountered in commercial operation and some additional margin might be required. Thus, it is concluded that a 15-percent margin is the smallest that could be tolerated by power-lift transports, and that this small margin would be acceptable because of the ability of STOL aircraft to increase both lift and flight path by power without changing airspeed or angle of attack.

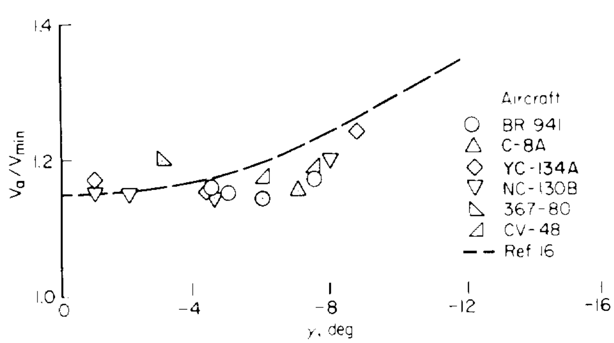


Figure 9.- Ratio of approach speed to minimum speed.

Some aircraft require an additional margin to flare at the steeper approach angles because power could not be increased rapidly enough to develop the required normal acceleration. The added margin is indicated in figure 9 by the increased ratio of approach speed to minimum speed as descent angle is increased. In this figure the flight-derived data points are compared to the theoretically derived curve of reference 16 for which it was assumed that the pilot would perform the flare utilizing 85 percent of the maximum lift capability

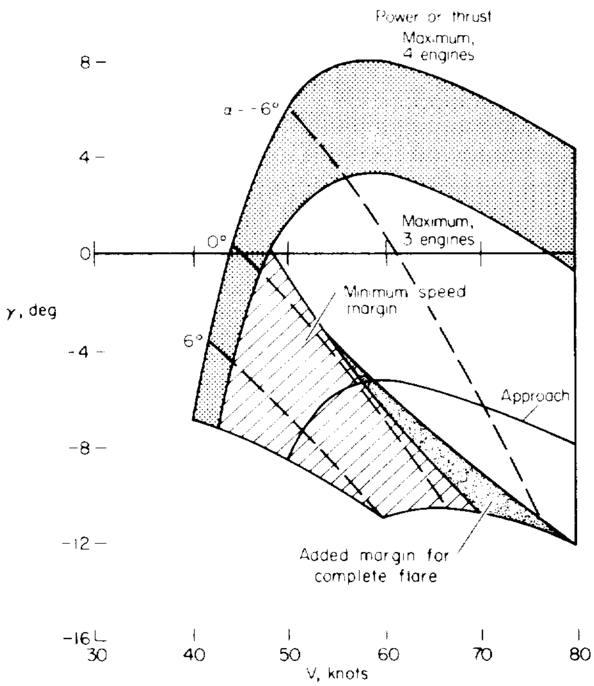


Figure 10.- Added margin for complete flare.

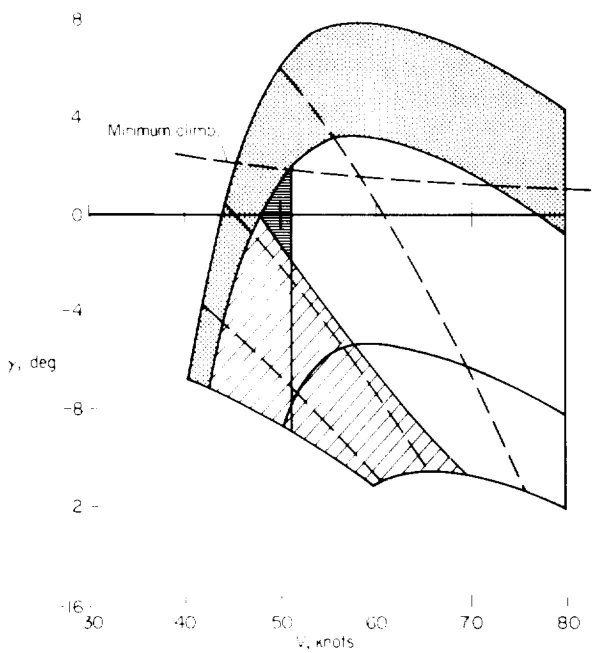


Figure 11.- Requirement for climb.

and touching down with an excess speed margin of 15 percent. This assumption is conservative for the aircraft tested. It should be pointed out that not all of the aircraft required a complete flare prior to touchdown. For example, the CV-48 required no flare at all; the BR-941 used only a "half flare" which reduced the descent velocity of 800 ft/min (at an approach angle of -8°) to a contact velocity of 300 ft/min. For these aircraft, the speed margin did not have to be increased for the flare. This procedure permits much greater touchdown accuracy and is less demanding of the pilot's judgment of the flare. It should be noted that these aircraft were not flared by the addition of power because of the relatively long lags in the engine-propeller control systems.

The envelope for an aircraft that requires complete flaring is compared in figure 10 with one that can utilize minimum speed margin because it has good energy-absorbing landing gear.

Available climb gradient in landing configuration.- It is necessary that the pilot have the option of discontinuing the approach at any time before he initiates the landing flare. Thus, tentative airworthiness standards (ref. 3) require a four-engine aircraft to have a steady climb gradient of not less than 1.8 percent or a rate of climb of not less than 200 ft/min in the landing configuration at the approach reference speed or flight-path reference criteria with the critical power-plant system inoperative. Comparison of figures 11 and 8 shows that this requirement has little effect on the envelope for the configuration chosen. As the propulsion system is further vectored and a greater portion of thrust is used to develop lift in steeper approaches, it will be difficult to meet a climb gradient without changing the effective angle of the thrust vector. This is illustrated in figure 12. The normal approach envelope is shown on the left, the envelope for steeper approach in

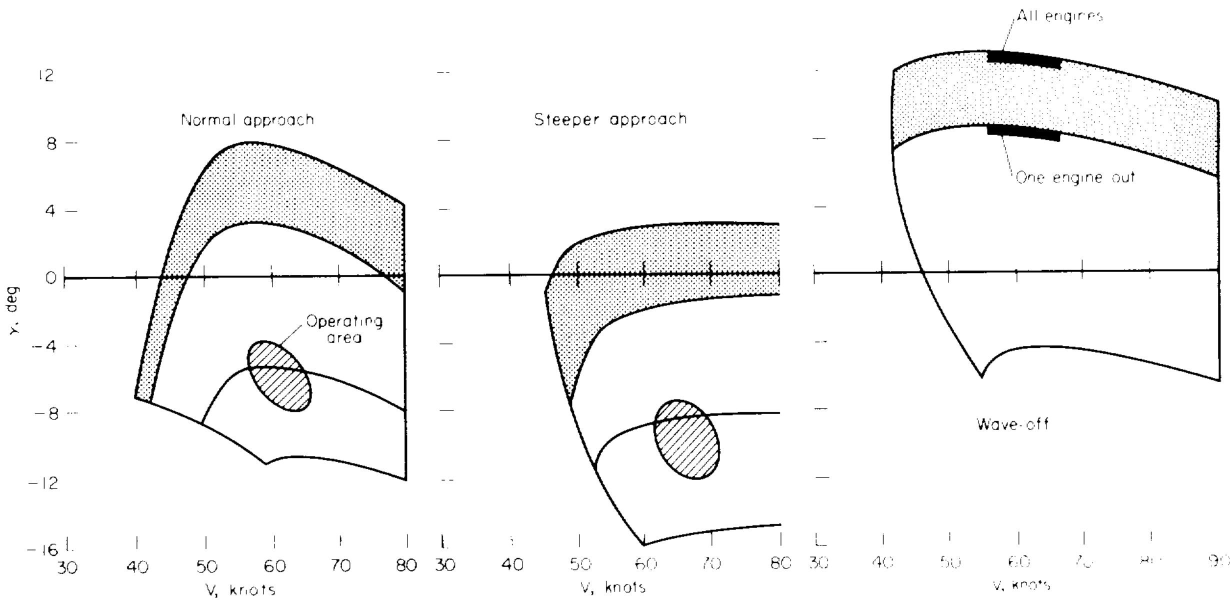


Figure 12.- Change in operational envelope with flap or thrust vector-type control.

the middle, and for wave-off, on the right. A positive climb gradient could not be obtained in the steeper approach configuration (middle figure) with an engine inoperative. To obtain a good positive gradient, the envelope was shifted vertically by changing the configuration (with a thumb switch mounted on the throttle) to the normal approach and then to the wave-off configuration (ref. 10). The minimum speed at each thrust level was relatively unchanged, the safety margins were not reduced, and the adverse moment changes were small. Under these conditions such a thrust vectoring change was satisfactory. Similar vectoring can be obtained by wing tilt, or direct vectoring of the thrusting source.

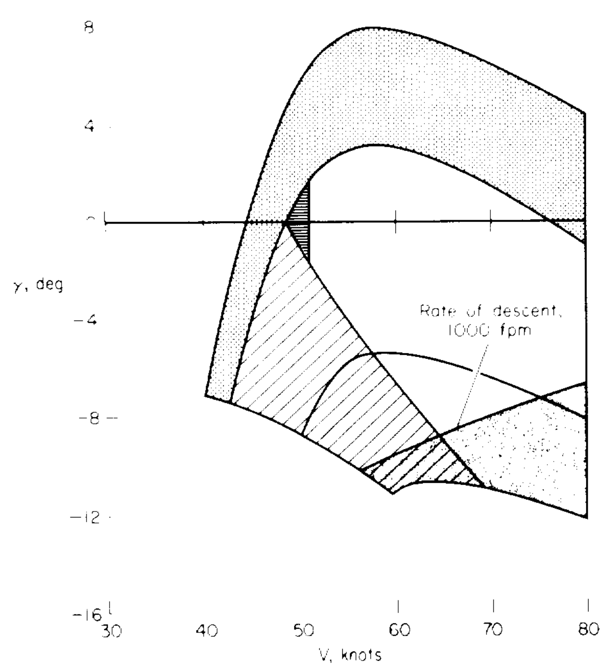


Figure 13.- Limit rate of descent.

<u>Maximum sink rate</u>.- The next restriction to the operating envelope is a limitation of sink rate to the maximum usable by the pilot while close to the ground. Experience with STOL and other aircraft has indicated that pilots are reluctant to exceed a rate of descent of 1000 ft/min when below an altitude of about 200 feet. Even in VFR conditions the time available for making decisions becomes too short and the judgment required to execute the flare properly becomes excessive. Application of this restriction to the operating envelope is shown in figure 13.

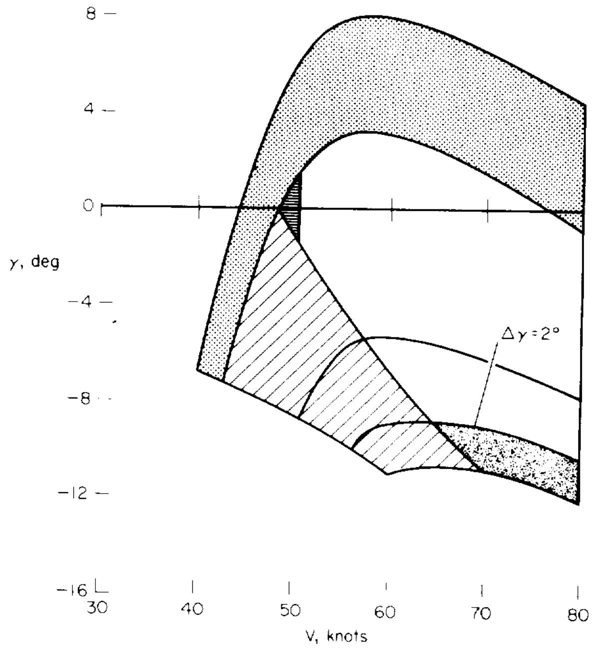


Figure 14.- Flight-path margins.

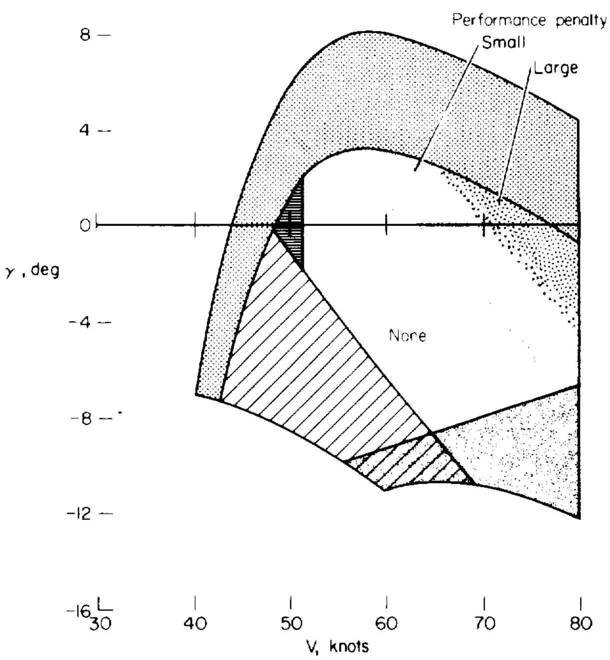


Figure 15.- Penalty due to improper touchdown attitude.

Flight-path adjustments.- Another important factor in the selection of the maximum approach angle of a STOL aircraft is that the pilot be provided a margin of descent capability that will allow him to adjust the flight path and touchdown point. This is particularly important for IFR approaches because if the pilot overshoots the glide slope during capture or rides high on it while tracking, he must be able to get back to the glide slope centerline without incurring a large speed increase. To perform this task it is necessary to change the flight path by 2°; this margin is shown in figure 14.

Touchdown attitude.- The final limitation (fig. 15) is not a restriction at all, but indicates that the landing distance may be increased disproportionately if the aircraft is not in a satisfactory touchdown attitude upon completion of the landing flare. This condition can arise when the approach speed is increased to obtain additional normal acceleration to flare the aircraft or to improve the handling characteristics in gusty environments. If the touchdown attitude is incorrect, it is necessary to increase angle of attack and attitude slowly as airspeed decreases until the touchdown can be satisfactorily made. This problem is not unique to STOL aircraft, but is more pronounced because of the relatively large changes in angle of attack that are associated with a given change in velocity (i.e., a 5-knot change in airspeed results in a 5° to 10° angle of attack change for balanced flight).

Considerations of asymmetry.- Figure 16, obtained from reference 5, shows the effect of a propulsion system failure that results in thrust asymmetry. The left-hand sketch shows the effect of an engine failure on the climb gradient and minimum control speed, and the right-hand sketch shows the result of imposing the previous

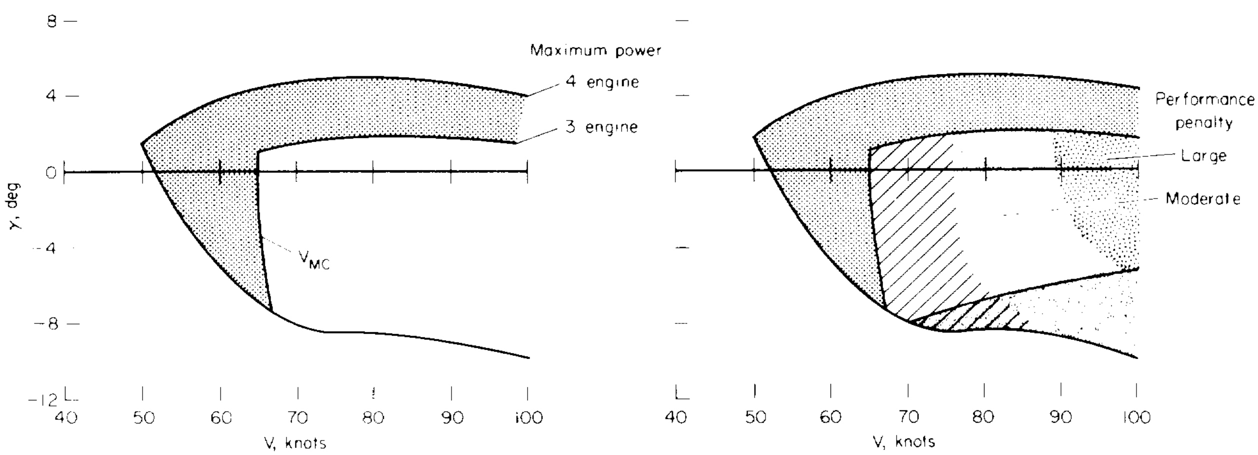


Figure 16.- Engine failure creating thrust asymmetry.

safety margins. It is seen that a propulsion system failure that causes asymmetry severely limits the STOL operation. Operating at the higher speeds required for safety also results in a significant performance penalty because of the improper attitude on touchdown (discussed in an earlier section). A further consideration is the deterioration of handling qualities when asymmetry occurs. It has been found that the minimum control speed for STOL aircraft can be limited by the lateral control as well as the directional control.

Summary of restrictions.- When all of the previous restrictions are imposed upon the operating envelope, they leave a rather small area from which a safe approach speed can be selected that will still produce reasonable performance. It is important that this situation not be misinterpreted to indicate a lack of flexibility. The small area remaining represents the steady-state situation from which transient excursions can be safely made into the shaded areas, and changing the configuration (as sketched in fig. 17) provides the wide latitude for adapting the aircraft to meet the needs dictated by the operational environment.

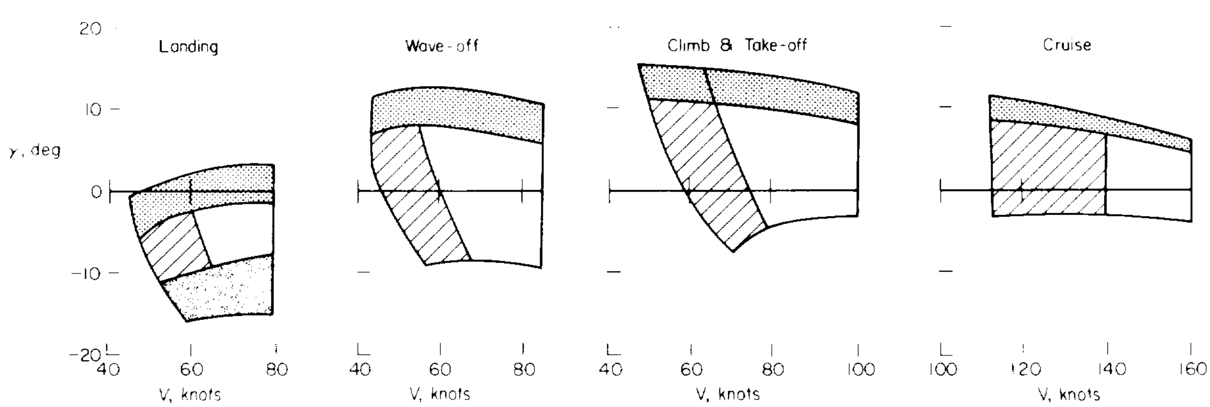


Figure 17.- Changing envelope to suit operational environment.

It is apparent that a single airspeed will not suffice as an adequate reference for all approach angles; however, the operational envelope can be examined to determine the best flight-path reference criteria. For the example STOL, lines of constant angle of attack are alined roughly parallel to the region of desired operation. The pilot chose an angle of attack near 0° to provide an adequate margin during the approach. This reference angle of attack had the added advantage of being independent of gross weight and configuration for the example aircraft.

Conclusions

STOL aircraft can utilize the propulsion system to develop a significant portion of the lift in the approach.

For the aircraft tested a representative level of thrust-to-weight in the approach was 0.2. In this mode, modulation of power produced more normal acceleration than horizontal acceleration.

A single airspeed could not be used as a reference for all flight-path angles of the aircraft examined because of the strong influence of power on the minimum speed. A method is presented whereby the low-speed flight envelope can be analyzed to determine a suitable speed, angle of attack, or other flight-path reference to establish a safe operation.

A minimum speed margin of 15 percent was used as protection from gusts and to assure maneuvering and flare capability. This small margin could only be used when large aerodynamic changes were not caused by an engine failure, when power produced an incremental normal acceleration of 0.2 g, and when modest flight-path angles were used in the approach. As flight-path angle was increased in the approach, the margin had to be increased to permit sufficient normal acceleration if a fully flared landing was required. A positive climb gradient was desired in the landing configuration with one engine inoperative; however, a configuration change can be permitted if there is no loss in lift and there are no adverse moments. When the aircraft is less than 200 feet above the runway, the sink rate should be less than 1000 ft/min. A flight-path margin of 2° is required to steepen the flight path beyond the normal approach value. Increased airspeed margins for increased normal acceleration can create performance penalties by causing improper touchdown attitude.

When large aerodynamic changes are caused by an engine failure comparable margins must be imposed on the characteristics after engine failure, and these restraints can limit STOL operation. The minimum control speed for STOL aircraft can be dictated by lateral control rather than directional control.

Landing Field Length

Consistency of performance.- In the previous section, margins were discussed that would provide safe approach and landing speeds for STOL aircraft. However, there are additional operational aspects that must be considered. For example, what can be done to assure that routine operation is possible under all runway and atmospheric conditions when a landing strip length, say 1500 feet, has been established? Further, is there some way that the demonstrated landing performance can give answers closer to the operational performance? Finally, how do handling qualities affect the ability to operate into STOL strips?

At the present time, insufficient flight data are available to verify the consistency in STOL landing performance over a range of approach angles and speeds, runway conditions, and atmospheric conditions. The effect of handling qualities on landing performance has not been studied systematically. It has been observed that, with a skilled pilot under favorable conditions and without constraint of a touchdown area, adverse handling qualities will not greatly affect the minimum landing distances, but will merely increase pilot workload. On the other hand, adverse handling qualities can significantly affect landing performance if the aircraft is disturbed by gusts, the touchdown area is confined, or the pilot is less skilled. Consequently, less importance should be placed on minimum landing distances, and more importance should be placed on measuring the landing distance with a realistic task. This is discussed in a later section.

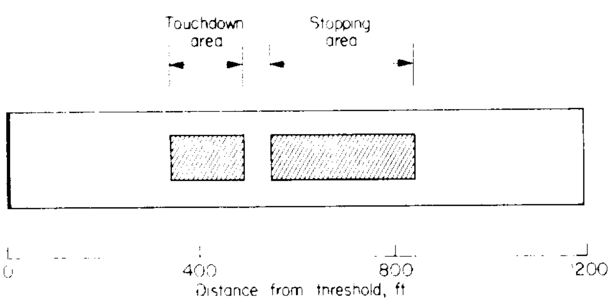


Figure 18.- Variation in landing distance over a wide variety of conditions.

Figure 18 shows grossly the landing performance that can be obtained with a STOL aircraft over a wide variety of conditions. This figure contains measurements of 60 landings of the Breguet 941 over a 50-foot simulated obstacle at the threshold. The measurements were made for different approach angles and various crosswinds, and included pilot training. The aircraft touched down 350 to 500 feet from the threshold and stopped 550 to 850 feet from the threshold. When it is realized that the range of stopping distances is only about three airplane lengths, it is seen that good STOL landing performance can be obtained under various operating conditions.

To examine the individual effects of different runway and braking conditions, landing techniques and pilot judgment, the landing performance over a 35-foot obstacle was calculated for an aircraft like the Breguet 941. Figure 19 shows the effect of different runway and braking conditions. The calculations were based on a 40,000-pound propeller-driven STOL aircraft

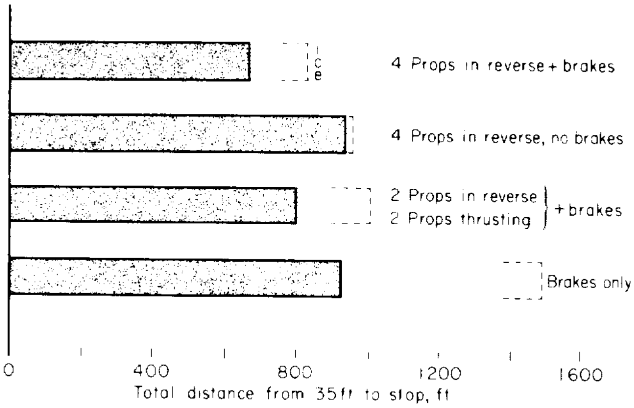


Figure 19.- Effect of different braking conditions on landing performance.

approaching on a 7-1/2° glide slope at 60 knots. It was assumed that one of four engines was inoperative (propulsion system is interconnected for symmetry and control), and there was a 1-second delay between touchdown and deceleration. The solid bars are for a dry-prepared surface while the dotted bars are for a slippery surface such as ice. The top bar is with all propellers reversed and antiskid brakes applied. The calculated distance over a 35-foot obstacle to a stopping point on a dry surface was 700 feet. This compares to the 550- to 850-foot distance over a 50-foot obstacle measured in flight for similar conditions. This performance was obtained with an approach speed consistent with all of the restrictions placed on the operating envelope presented earlier. Thus, good STOL performance can be obtained with a high degree of safety. For this case, the average deceleration during the ground roll was about 0.4 g which was not uncomfortable to the passengers because the deceleration increased smoothly. An icy surface is estimated to increase the distance by only 150 feet, about two airplane lengths. The second bar is for all propellers reversed and no brakes. The third bar is for the condition of one propeller not reversing; the opposite propeller is positioned at the same blade angle by safety features incorporated with the interconnect. The last bar is for brakes only, with the propellers producing near zero thrust. For this case, where propellers are not reversed, a slick surface like ice is quite detrimental. Figure 19 shows that the landing performance does not change appreciably over a wide range of failure and runway conditions provided symmetrical reversing is utilized.

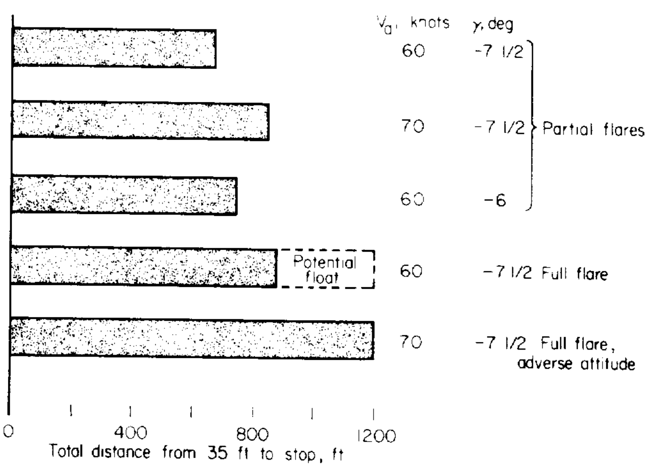


Figure 20.- Effect of judgement and techniques on landing performance.

Figure 20 shows the effect of different piloting techniques or judgement. The top bar is for the basic case shown in the previous figure. The next bar shows what happens when the pilot is 10 knots fast, or there is a 10-knot tail wind. The increase is only 150 feet, less than two airplane lengths. The next bar reflects the small increase in air distance if the airplane is flown on a 6° glide angle instead of a 7-1/2° glide angle. All of these distances are for partially flared landings to reduce the vertical velocity at touchdown to about 5 ft/sec. The next two bars represent the total landing distance for fully flared landings. There is a small increase in air distance; however, this is not the main concern. A fully flared landing must be initiated at a greater height above the runway, and it is difficult to judge precisely where the aircraft will touchdown. If the aircraft is rotated too soon or too much, the floating distance will be a large portion of the ground roll. It was noted in the previous section that if an added speed margin were applied, the contact attitude could be quite unfavorable and it would be necessary to decelerate in the air; this effect on performance is shown in the last bar.

Demonstration of landing performance.- The landing performance for STOL aircraft should be demonstrated under conditions close to an operational environment and factors pertinent to that craft should be used for determining the operational field length. The flight path should be constrained to a designated obstacle clearance angle as well as a designated landing area, and a task should be included to expose adverse handling characteristics. This is in contrast to the current procedure of FAR 25 and 121 (refs. 17 and 18) of permitting a "maximum effort" landing demonstration anywhere on a dry runway and then dividing this distance by 0.6 to cover operational environments. A different method is recommended because one factor cannot cover the effects of gust, wind shear, runway condition, and landing technique for all STOL aircraft. One possible method of demonstrating the performance for STOL aircraft is shown on figure 21.

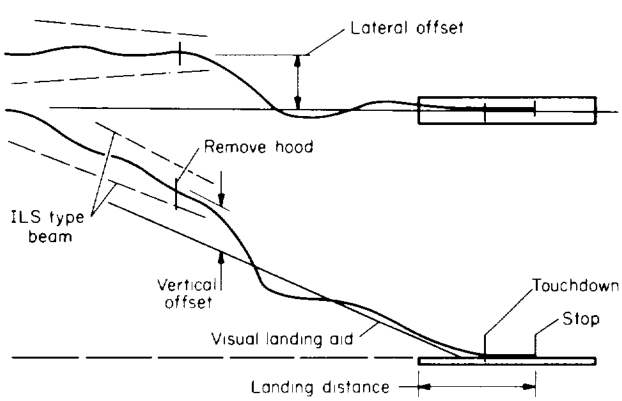


Figure 21.- Demonstration of landing performance.

The top part of this figure represents a plan view of the approach and landing area, and the bottom an elevation of the same area. The solid lines represent the center line of a visual landing aid set at the glide angle desired for certification and intercepting the runway near the intended touchdown point. The short dashed lines represent an ILS type system set at the desired flight-path angle but offset from the visual aid. The pilot would start an ILS approach, and at an altitude of about 200 feet, he would remove his hood, correct the offset, stabilize, and continue to a full stop. Another possible method might be to offset the ILS at an angle, say 20°, rather than a lateral distance. In either case, a specified number of landings could then be used to determine the demonstrated landing performance. Phototheodolite coverage would document the performance and disqualify landings made when the aircraft went below the designated obstruction angle.

Field length factor.- A singular factor such as 1/0.6 should not be applied to the demonstrated performance to obtain an operational field length. Instead, factors should account for the method of operation (e.g., partial versus fully flared landing), sensitivity to disturbance (e.g., aspect ratio and wing loading), runway surface, and whether or not reverse thrust is used.

At the present time, insufficient systematic data have been obtained to formulate field length factors. If the critical case is with one engine inoperative and only two propellers in reverse, according to figures 18 and 19, the average demonstrated landing would probably be about 900 feet with a partial flare. An appropriate field length considering cross winds, tail winds, and wet runway, would be about 1200 feet if satisfactory handling qualities were provided. The corresponding factor would then be about 1/0.75.

A visual guidance system should also be used at the airport runways so that the pilot has a flight-path reference at least to the threshold. Such a reference is an important assistance in steep descents to avoid large last-minute corrections and to safely utilize the maximum performance of the aircraft.

Obstacle clearance angle.- Since STOL aircraft will operate in restricted airspace, appropriate obstacle clearance margins are of importance. There are at present insufficient data to determine safe margins. When examining the aircraft descent capability, not only must the planned approach flight path and obstacle clearance margin be considered but an additional descent margin of 2° is necessary for correcting tracking errors or tail wind (discussed earlier).

Take-Off Field Length

Take-off gradient.- Performing STOL take-offs with a steep gradient profile requires a large thrust-weight ratio, and a high acceleration occurs even at lift-off speed. This is shown in figure 22 by a take-off time history from reference 10.

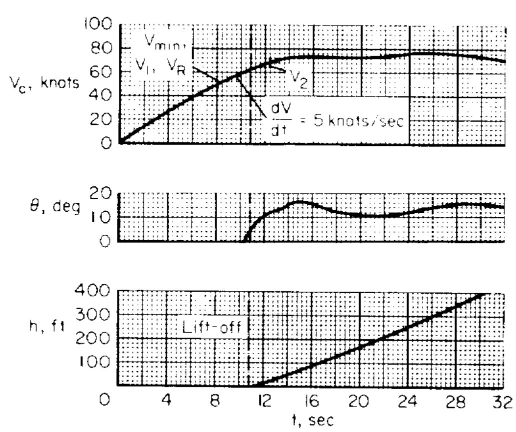


Figure 22.- STOL take-off.

The time from brake release to rotation speed, V_R, computed critical decision speed V_1, and optimum climb speed, V_2, is short, and since the propulsion system was interconnected, recognition of an engine failure was difficult. The primary effect of an engine failure on this aircraft was a reduced climb gradient.

The minimum climb gradient will have to include an appropriate obstacle clearance gradient which will be related to the area in which the aircraft is intended to be operated. For a useful STOL aircraft, it seems reasonable to expect the safe take-off climb gradient to be of the same magnitude as the landing gradient; therefore, it would be expected that gradients of at least 6° will be required when an engine is inoperative.

Take off field length factor.- For a steep gradient STOL aircraft a large thrust-weight ratio will be installed, and the runway conditions are not as critical as they have been with some subsonic jet transports; however, the rejected take-off and one-engine-out climb performance will have to be examined as in current regulations (refs. 17 and 18). For the example STOL craft used in the previous sketch the take-off distance to 35 feet with an engine stopped at V_R is 900 feet. The corresponding start-stop distance was computed to be 700 feet. In comparison, the take-off distance to 35 feet with all engines operative is 800 feet.

Terminal Area Operation

Since STOL aircraft will be required to operate in restricted airspace some knowledge of the minimum pattern size that can be safely flown is needed. Examples are provided in reference 10. Under VFR conditions, it was found that 90° turns into the final approach could be performed as low as 300 feet at 65 knots and the maximum operational bank angle was about 30°. This corresponded to a radius of less than 1000 feet.

The take-offs and climbouts were simple to perform under VFR or IFR conditions; the procedures and handling characteristics were similar to those for a conventional turboprop transport.

The importance of providing good handling qualities for IFR operation was noted in references 7 and 10. When these were provided, steep approaches at STOL speeds could be safely made in IFR conditions to altitudes of 200 feet with unsophisticated guidance or display systems.

Conclusions

Less emphasis should be placed on demonstrating maximum performance. More importance should be placed on demonstrating consistent performance with a task that simulates environmental conditions that may be encountered in routine commercial operation and that exposes adverse handling characteristics. Insufficient systematic information is available for relating field length factors to operational considerations and handling qualities.

DISCUSSION OF HANDLING QUALITIES

Background

Several reports have been published on handling qualities criteria for V/STOL aircraft (e.g., refs. 19-21); however, these have been primarily oriented toward military missions and requirements, and their acceptance has been limited because of the inability to verify the criteria by flight experience with representative V/STOL aircraft. The present report is directed toward providing the regulatory agencies with criteria for safe operation of STOL aircraft in a commercial environment.

The criteria presented herein are based on pilot opinion and quantitative data accumulated from flight investigations of STOL aircraft. It was assumed that these aircraft will operate under instrument conditions and will be required to maneuver in confined areas where turbulence and wind shears are likely to be encountered. Criteria are not presented for each facet of handling qualities because there was insufficient data. The major emphasis and greatest quantity of data is on the lateral-directional handling in the landing-approach regime because this area has caused the greatest difficulty and is the most demanding portion of the flight. Limited information is given on longitudinal handling as well as on the wave-off and take-off regimes.

The criteria are presented separately from the data used in their formulation. The section containing the data presents considerable discussion to substantiate the criteria and to show how they were formulated. Criteria related to aircraft response to control input will be presented first because it is most important that the aircraft have a good control system and good control characteristics in order to operate satisfactorily in the severe environment anticipated with the low levels of stability and damping normally present at STOL speeds. A succeeding section presents criteria related to aircraft response to external disturbances.

Since handling qualities are judged by pilots' opinions, criteria were formulated so that they could be easily recognized and appreciated by the pilot, readily evaluated for compliance, and they would include the effect of factors that influence the response or behavior of the aircraft. The task of providing meaningful criteria is compromised by many problems which include the difficulty in measuring the parameter in question, the interaction of several variables upon pilot opinion, the inability to vary the pertinent parameters systematically, and the fact that the pilot seldom has the opportunity to evaluate the aircraft behavior under all environmental conditions. It must be recognized that the handling qualities criteria given are limited in scope and will require continued revision as new aircraft concepts with more advanced control and stabilization systems are developed and tested.

Level of Criteria

A question arises as to which level of pilot acceptability the criteria should reflect for commercial transport operation. Two levels have been indicated in the criteria: one level should be exceeded to obtain satisfactory handling in IFR as well as in VFR flight; the other represents the lowest level for a particular parameter that a pilot can tolerate without significantly compromising the task or mission. In this report the pilot's opinion of a specific parameter or aircraft behavior was evaluated according to the Cooper Rating Scale first presented in 1957 (ref. 22). This scale, shown below, is a shorthand method of indicating pilot opinion; however it had several shortcomings when these handling quality evaluations were related to commercial transports. These shortcomings included the introduction of stability augmentation and undefined failure modes, the concept of normal and

Operating conditions	Adjective rating	Numerical rating	Description	Primary mission accomplished	Can be landed
Normal operation	Satisfactory	1	Excellent, includes optimum	Yes	Yes
		2	Good, pleasant to fly	Yes	Yes
		3	Satisfactory, but with some mildly unpleasant characteristics	Yes	Yes
Emergency operation	Unsatisfactory	4	Acceptable, but with unpleasant characteristics	Yes	Yes
		5	Unacceptable for normal operation	Doubtful	Yes
		6	Acceptable for emergency condition only[1]	Doubtful	Yes
No operation	Unacceptable	7	Unacceptable even for emergency condition[1]	No	Doubtful
		8	Unacceptable - dangerous	No	No
		9	Unacceptable - uncontrollable	No	No
	Catastrophic	10	Motions possibly violent enough to prevent pilot escape	No	No

[1]Failure of a stability augmenter.

emergency operation, and the separation of the landing task from the primary mission. Additional discussions are contained in reference 23, and a revised scale is presented. The revised scale could not be used in this report because the majority of data were drawn from previously published reports. It was determined that the level for satisfactory handling corresponds to a rating of 3-1/2 for both the original Cooper scale and the revised scale; the second lower level of criteria corresponds to a rating of 5 to 5-1/2 on the original Cooper scale and a 6-1/2 on the new scale.

If the aircraft's handling qualities exceed the satisfactory level for each criterion, the aircraft should be capable of performing its mission under a wide range of environmental conditions. This is not true if the aircraft has several parameters that fall into the lower tolerable level of criteria. Then the pilot workload might become high enough to endanger the safety of the aircraft even though each parameter could be tolerated by itself. A method has not been found to sum or weigh properly these ratings of individual characteristics to arrive at an overall rating for complete mission phases such as "approach" or "landing"; a separate judgment and rating is required by the pilot.

Criteria for Aircraft Response to Control Input

Factors included in criteria.- The following comments pertain to all axes; in succeeding sections detailed discussion will be made for each axis.

Control power: The need for control can generally be divided into three separate requirements; trim, maneuverability, and stabilization (largely due to environmental disturbances). In some cases, these requirements may be additive; however, in most of the STOL aircraft evaluated, they appear to be dominated in each of the axes by only one of the requirements. It is recognized that these requirements may be different for aircraft configurations which are not similar to those evaluated, and that they may be changed by stability augmentation systems. The criteria are not related to gross weight because it has been assumed that the aircraft of interest are in the 30,000 to 100,000 lb range where the control power requirements are fairly constant.

Control sensitivity: In addition to adequate control power, it has been found that control sensitivity plays an important role in the pilot's ability to control the aircraft. The maximum control deflections presented in the criteria are not meant to provide optimum control sensitivity of the system but rather to define a lower limit, assuming that the aircraft response to control deflection is linear.

Linearity: The requirement for linear aircraft response to control deflection is not well defined. Figure 23 shows three types of system characteristics that were present on the STOL aircraft tested.

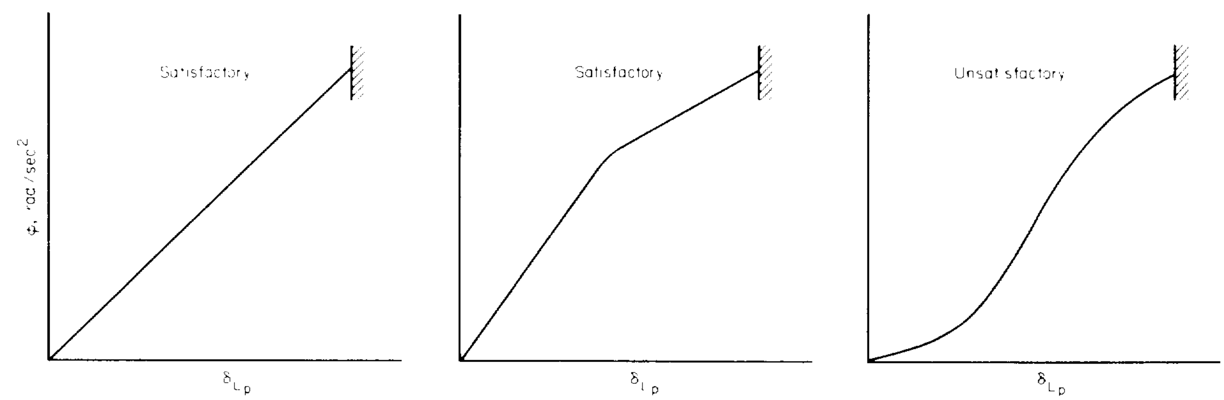


Figure 23.- Illustration of different control systems.

When an abrupt increase in roll response occurs as the control deflection is increased, as in the right-hand sketch, there is a marked tendency for the pilot to overcontrol the aircraft laterally; this tendency has not been noted in those aircraft for which the nonlinearity was in the opposite direction, as in the middle sketch. Although the pilots have not commented on undesirable nonlinearities in the other axes, similar results would be expected.

Mechanical characteristics of control systems: The primary flight control systems of STOL-aircraft should be designed so that the pilot can easily operate them with one hand while he adjusts thrust or power to control flight path with the other. Such items as breakout forces, friction, force gradients, sensitivity, control harmony, linearity, lags, and inertia all influence the pilot's opinion of the aircraft's handling qualities. In some cases poor mechanical characteristics have completely masked the aircraft's inherent stability and the pilot's impression of controllability.

The maximum control forces specified in the criteria are consistent with the concept of one-hand operation. They combine the individual effects of breakout, friction, inertia, and gradient forces; simplified criteria are not intended to imply that each of these items is not important in its own right. The mechanical characteristics of the control system of each of the aircraft tested and some comments are presented in table III.

Cross coupling: Cross coupling is usually covered in the discussion of stability; however, it will be included in the response section because it is generally apparent to the pilot as a result of his control inputs. The intent of the criteria is to minimize undesirable disturbances about and along axes other than the one the pilot is controlling.

Apparent damping: The criteria for damping covered in the response section includes the effect of control system lags which the pilot finds difficult to discern and separate from the aerodynamic damping of the vehicle. The resulting apparent damping affects the pilot's ability to control the attitude of the aircraft precisely.

Lateral control criteria.- The following table presents the proposed criteria for aircraft response to lateral control inputs at the STOL reference speed or angle of attack.

Item	Parameter to be measured	Level for satisfactory operation	Level for safe operation
1. Control power	Time to 30° bank angle	No more than 2.4 sec	No more than 2.9 sec
	Roll acceleration within 1/2 sec	More than 0.4 rad/sec^2	More than 0.3 rad/sec^2
	Maximum control deflection	No more than 60° wheel deflection or 5-in. stick deflection	No more than 90° wheel deflection or 7-in. stick deflection
2. Force	Maximum force to achieve item 1	20 lb	40 lb
3. Linearity	Roll acceleration per unit stick deflection	Should not increase	Insufficient data
4. Cross coupling	$(\Delta\beta/\Delta\phi)_{max}$	0.3	0.6
	$\Delta\theta$	Not noticeable	Not objectionable
	a_n/g	Less than -0.1	Less than -0.2
5. Apparent roll damping	Number of control reversals to stabilize	No more than 2	No tendency for pilot induced oscillation

The maneuvers to test compliance with all criteria should be initiated from trimmed, wings-level, nonturning flight, and should be performed in both directions. Compliance with the criteria of items 1 through 3 should be demonstrated by performing abrupt rudder-fixed, lateral control steps of increasing magnitude to the limit of control authority or until the required response is achieved. The control power criteria were developed to provide some measure of the ability to maintain the desired bank angle in turbulent air. Control in turbulence has been the most critical requirement for lateral control at the approach and take-off speeds. The time should be measured from the initiation of the control action by the pilot.

An engine failure on a STOL aircraft without an interconnected propulsion system can cause an asymmetric rolling moment that may be more critical than the yawing moment, particularly if a large part of the lift is developed by the propulsion system (refs. 4, 5, and 12). To maneuver adequately during an approach with an engine inoperative, sufficient lateral control must remain to satisfy the criteria for safe operation with the remaining engines at the power level required for the selected approach flight path angle. Less maneuvering is required during the wave-off and take off, and the lateral and directional control with an engine inoperative can be reduced to the level implied in reference 3.

Compliance with items 4 and 5 should be demonstrated by performing abrupt, rudder-fixed turn entries to bank angles of at least 20°. STOL aircraft which have low directional stability can develop high sideslip angles during maneuvering which hinder the pilot's ability to make precise heading changes and accurately control sideslip during crosswind landings. This problem of cross coupling (turn coordination or "adverse yaw") is best correlated by the ratio of peak sideslip excursion to the bank angle ($\Delta\beta/\Delta\phi$) developed during rapid turn entries.

Lift losses caused by spoilers used for lateral control have created minor coupling problems. Such losses have been related to the incremental normal acceleration, measured at the center of gravity, with maximum control deflection.

Apparent roll damping cannot be easily defined by classical means because it includes the effects of both the aerodynamic characteristics of the airframe and the mechanical characteristics of the control system. It becomes troublesome to the pilot when he cannot easily arrest and stabilize an established roll rate. In the more extreme case, it may be manifested by a continuous roll oscillation which is sustained by the pilot's control activity. Because of insufficient knowledge of the interaction of these characteristics, the criterion is presented in a qualitative rather than in a quantitative term.

Directional control criteria.- The following table presents the proposed criteria for aircraft response to directional control inputs. Data to substantiate these criteria are presented in a later section. Compliance with the criteria should be demonstrated by steady-state sideslips performed at a constant heading and by abrupt rudder pedal steps with lateral control fixed at the trim position. Tests should be performed in both directions.

The most critical requirement for directional control has been the ability to trim the aircraft, and this has been primarily manifested in compensating for a crosswind component in the approach and landing. Figure 24 shows that large crab, or sideslip angles, are required for moderate crosswinds at STOL speeds. Since this has serious design implications, and since the crosswind that may be encountered is unknown, the control power criteria for a satisfactory level of steady-state sideslip angle is not given in a quantitative form. The criteria also specify an angular response to rudder pedal deflection. This is important to enable the pilot to rapidly decrab

Item	Parameter to be measured	Level for satisfactory operation	Level for safe operation
1. Control power	Steady-state sideslip angle	$\beta = \sin^{-1}\left(\frac{V_{xw}}{V}\right)$	No less than 15°
	Time for 15° change in heading	2.2 sec	3.1 sec
	Maximum pedal deflection	At least ±2-1/2 in.	At least ±2-1/2 in.
2. Force	Force to achieve item 1	Greater than 50 lb, but less than 100 lb	Less than 150 lb
3. Linearity	Variation of sideslip angle with pedal deflection	Linear to specified sideslip angle. At larger values, increased pedal deflection for increased sideslip	
4. Cross coupling	Effective dihedral	Positive, but less than 50 percent maximum lateral control power	Positive, but less than 75 percent maximum lateral control
	Response about longitudinal axis	Not noticeable	Not objectionable

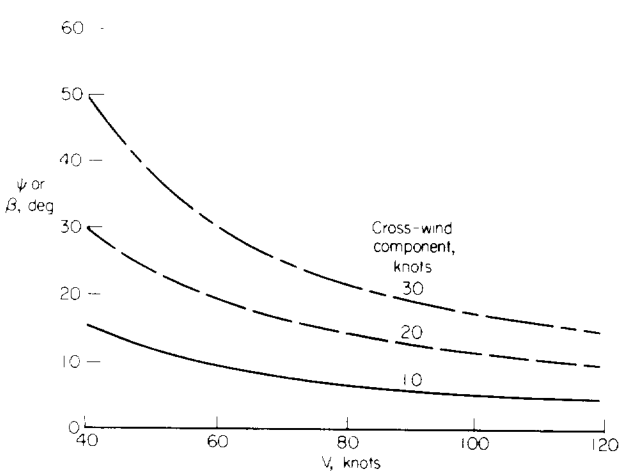


Figure 24.- Effect of cross wind at low airspeeds.

the aircraft prior to touchdown and to quickly reduce unwanted sideslip angles that occur during maneuvering. The time for a 15° heading change was chosen as an indication of the directional response; this time should be measured from initiation of a pilot input starting at trim sideslip angle.

Another critical requirement is that the directional control counteract an asymmetric moment caused by a propulsion-system failure. For the STOL aircraft without interconnected propulsion systems, large asymmetric moments occurred with a powerplant failure; it is proposed that sufficient control be available after failure to satisfy the level for safe operation specified in the previous table.

The most prevalent cross-coupling effect resulting from directional control input is the lateral response or dihedral effect; the concern is that sufficient lateral control power be available at the maximum sideslip angle specified to insure adequate control of bank angle.

Longitudinal control criteria.- The following table presents the proposed criteria for satisfactory aircraft response to longitudinal control inputs. All the aircraft tested had adequate response and damping; therefore, it was not possible to define a lower acceptable level. Compliance with these criteria should be demonstrated by performing abrupt longitudinal steps and abrupt attitude steps of at least 10°.

Item	Parameter to be measured	Level for satisfactory operation	Level for safe operation
1. Control power	Time for 10° attitude change	Less than 1.2 sec	Insufficient information to provide criteria
	Pitch acceleration within 1 sec	More than 0.5 rad/sec^2	
	Maximum control deflection	No more than ±5-in. column deflection	
2. Force	Maximum force to achieve item 1	40 lb	
3. Linearity	Pitching acceleration per unit stick displacement	Should not increase	
4. Apparent damping	Number of control reversals to stabilize	No more than one	

The longitudinal control power requirements may be dominated by either maneuvering or trimming depending upon the aircraft configuration and the nature of the approach and landing technique that is used. The maneuvers that required the greater longitudinal control were rotation at take-off and flaring at landing. The level of control power specified in the criteria should be satisfactory for any longitudinal maneuvering that might be considered for a commercial transport. When abrupt attitude changes may be objectionable, other methods of developing normal acceleration should be considered; criteria for other methods are discussed in the section on flight-path control.

The longitudinal control system must also be capable of trimming the aircraft throughout the flight envelope. It must be possible to attain the minimum speed as defined in the section "Minimum Speed Margins" under all conditions of weight and loading for which the airplane will be operated. Sufficient nose-down pitching response must be available at the minimum speed under all power conditions to effect a satisfactory recovery. An additional requirement is needed to insure that the pitch attitude can be controlled adequately prior to touchdown. For the latter requirement it is proposed that the longitudinal control be sufficient to trim the aircraft at the desired attitude in ground effect at a speed corresponding to the approach reference criterion minus 5 knots.

The longitudinal control requirements for sensitivity, force, linearity, and apparent damping are comparable to those for lateral control. Although it is noted that harmony between lateral and longitudinal control should exist, no related criteria are presented.

Flight-path control criteria.- One of the characteristics of powered-lift aircraft is that less normal acceleration is available from longitudinal control, and the pilot must use additional methods of developing normal acceleration for controlling flight path. Some consideration must be given to the response characteristics of these other methods of control so that the pilot can adequately control the aircraft's flight path, particularly during the approach and landing. The following criteria are divided into three modes of flight-path control:

Mode A. For flare and touchdown control when an incremental acceleration of less than 0.15 g can be developed by longitudinal control.

Mode B. For flight-path tracking when an incremental acceleration of more than 0.15 g but less than 0.30 g can be developed by longitudinal control.

Mode C. For gross flight-path changes including wave off, regardless of the normal acceleration developed by longitudinal control.

In order to determine whether the criteria for Mode A or Mode B apply, abrupt longitudinal control steps should be performed with the aircraft trimmed at conditions for the flight-path angle selected for the performance demonstration. Mode C applies to all aircraft. Compliance with the criteria listed in the table should be demonstrated by performing steps with the flight-path control. The aircraft attitude should be maintained constant with the longitudinal control; the initial conditions are with the aircraft trimmed at the flight-path angle selected for the performance demonstration. The acceleration should be measured at or near the aircraft center of gravity.

Item	Mode	Parameter to be measured	Level for satisfactory operation	Level for safe operation
1. Control power	A	Incremental normal acceleration	±0.1 g	Insufficient data
	B	Incremental normal acceleration	±0.1 g	Insufficient data
	C	Steady-state climb angle	6°	200 ft/min
	All	Incremental descent angle	2° greater than selected approach angle	Insufficient data
2. Response time	A	Aircraft response	Achieve IA in less than 0.5 sec	Insufficient data
	B	Aircraft response	Achieve IB in less than 1.5 sec	Insufficient data
	C	Aircraft response	Achieve IC in less than 2.0 sec	Achieve IC in less than 4.0 sec
3. Cross coupling	All	Pitching moment	Not noticeable	Not objectionable

Substantiation of Control Criteria

Lateral control power.- Pilots have been more critical of the control of STOL aircraft about the lateral axis than about the other axes. Precise control is required because small bank angles generate large yaw rates at low speeds which quickly produce heading excursions. The ability to maintain the desired bank angle in turbulent air has been the most critical requirement for lateral control of STOL aircraft at take-off and landing speeds, at least for moderate sized aircraft evaluated with all engines operating. This was concluded because less than 40 percent of the available control was used during extensive maneuvering when a satisfactory level of control was present. Little lateral trim was needed for crosswind landings, and little or no trim was required for thrust asymmetry because all powerplants were operative during the evaluation.

Figure 25 summarizes the lateral control power measured and evaluated with the various STOL aircraft at approach and take-off speeds. The results are given in terms of maximum angular-acceleration capability of the aircraft; that is, the acceleration produced by a step input with zero rate of roll. The values were measured in flight primarily by aileron reversals as discussed in reference 24. The angular acceleration presented in these figures cannot be related directly to the aircraft response nor to the pilot's impression of controllability; items such as the mechanical characteristics of the control system, pilot's recognition of needed corrective measures,

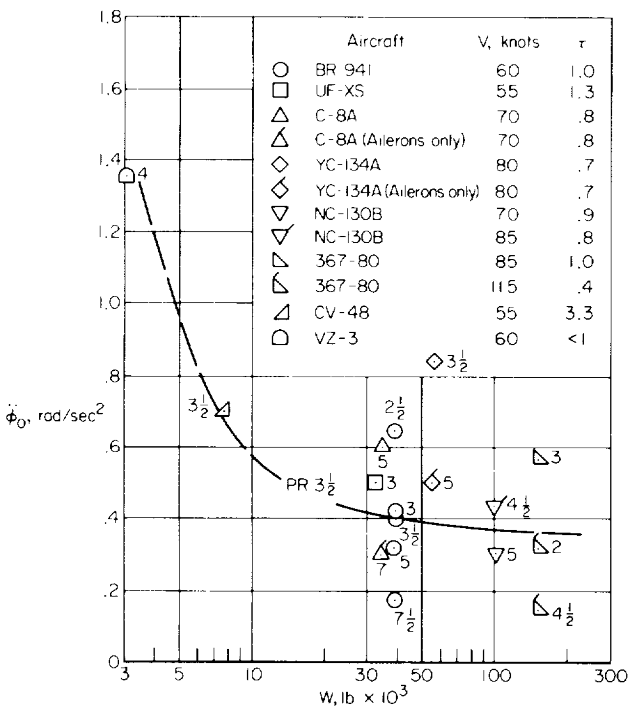


Figure 25.- Lateral acceleration. Pilot rating next to symbol.

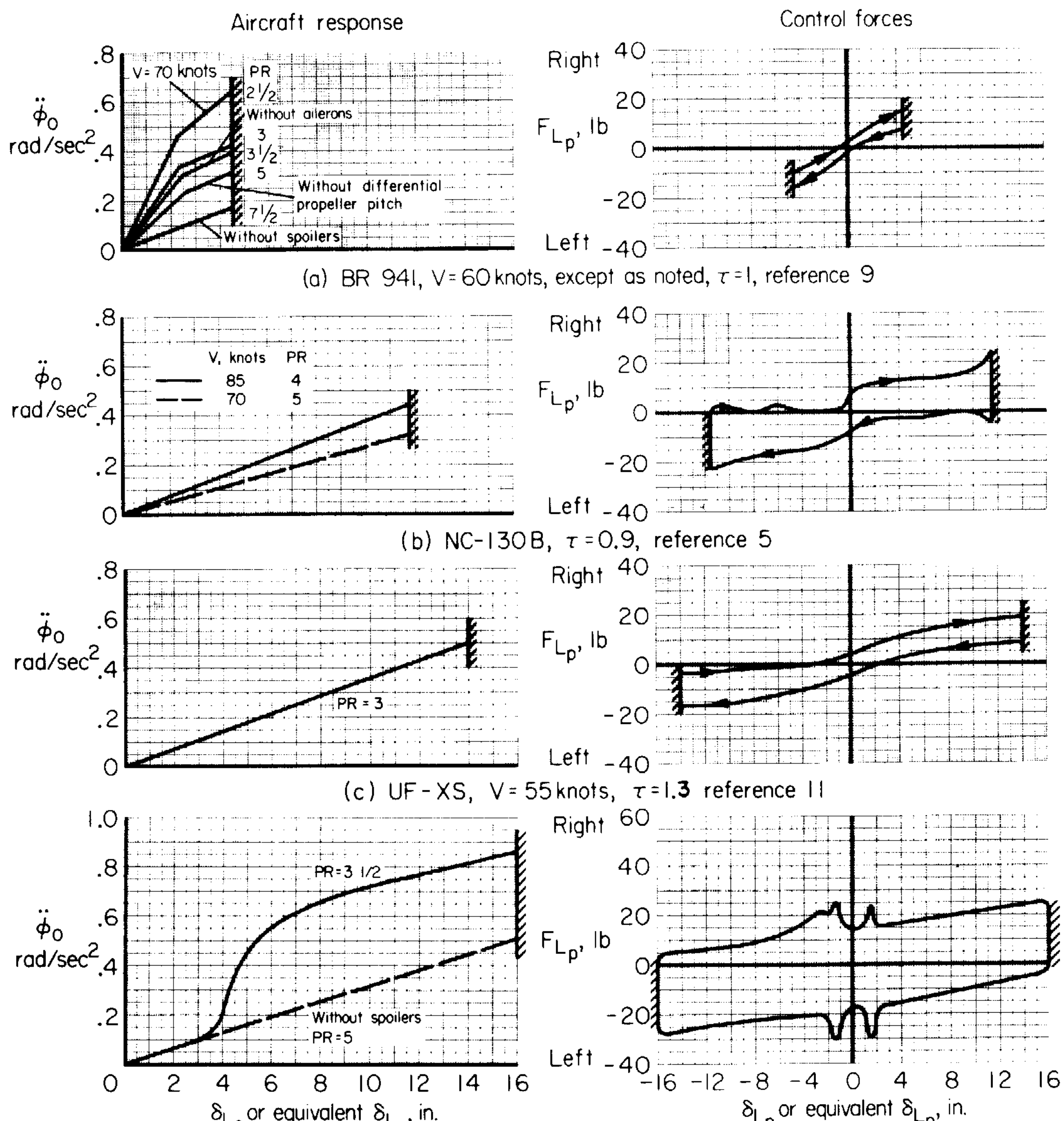
aircraft damping, cross coupling, and sensitivity to gust disturbances all play a part in lateral controllability. The interaction and relative importance of these factors is not accurately known; however, these factors were considered in fairing the data of figure 25 and will be discussed to some extent in the following paragraphs. The faired data represent the relation of pilot rating and acceleration for a common damping (τ = 1.0) and a good control system. The control power criteria presented earlier were not related to gross weight because it has been assumed that the aircraft of interest are in the 30,000 to 100,000 lb range where the control power requirement is fairly constant.

The angular acceleration and force characteristics of the different STOL aircraft are given in figure 26 along with a summary of comments on these characteristics. Figure 26(a) contains data from the BR 941 tests (ref. 9) in which the control power was changed by different combinations of spoilers, ailerons, and differential propeller pitch and was evaluated at approach and take-off speeds. Satisfactory ratings were given for those configurations providing at least 0.4 rad/sec^2. Although the control sensitivity (control power per inch deflection) was different for each configuration, the sensitivity was satisfactory for all cases tested with the possible exception of that rated 7-1/2, and should not affect the control power rating. Subsequent tests with this aircraft in IFR operation and moderate turbulence (ref. 10) showed that 0.4 rad/sec^2 was satisfactory under the more adverse test conditions.

The ratings of the NC-130B (fig. 26(b)) reflected low sensitivity. These ratings were based on an evaluation of IFR approaches in gusty weather with all engines operative. At 70 knots almost full lateral control was required to balance an inoperative engine because the propellers were not interconnected and considerable powered lift existed. Insufficient control remained to maneuver the aircraft during approach and landing; therefore landings were not performed with an inoperative engine.

The UF-XS (fig. 26(c)) had satisfactory characteristics in the approach condition with all engines operative. The evaluation of control was limited, and engine-out tests were not permitted.

Even though large lateral-control power was available on the YC-134A with spoilers and ailerons (fig. 26(d)), precise control of the aircraft was difficult because of the rapid increase in response at 30° wheel position, the



(a) BR 941, V = 60 knots, except as noted, τ = 1, reference 9

(b) NC-130B, τ = 0.9, reference 5

(c) UF-XS, V = 55 knots, τ = 1.3 reference 11

(d) YC-134 A, V = 80 knots, τ = 0.7, reference 4

Comments

(a)

1. Stick-type control, satisfactory geometry
2. Fully powered control system, ground measured forces
3. Satisfactory forces
4. Satisfactory aircraft response with normal landing and take-off configuration
5. Unsatisfactory lag due to rate limiting propeller pitch change in later tests (ref 10)

(b)

1. Wheel deflection ± 90°, too large
2. Powered control system with high friction between wheel and actuators, ground measured forces
3. Unsatisfactory force characteristics
4. Unsatisfactory aircraft response, probably due to low sensitivity and high friction

(c)

1. Wheel deflection ± 105°, too large
2. Powered control system, ground measured forces
3. Satisfactory forces
4. Satisfactory response

(d)

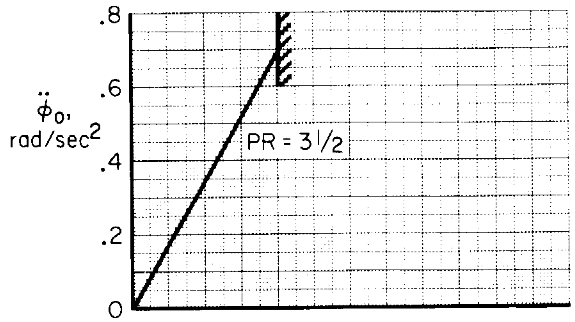
1. Wheel deflection ± 120°, too large
2. Mechanical control system, ground measured forces not really indicative of in-flight forces
3. Unsatisfactory forces
4. Unsatisfactory nonlinear forces and response
5. High inertia

Figure 26.- Lateral control characteristics.

Aircraft response

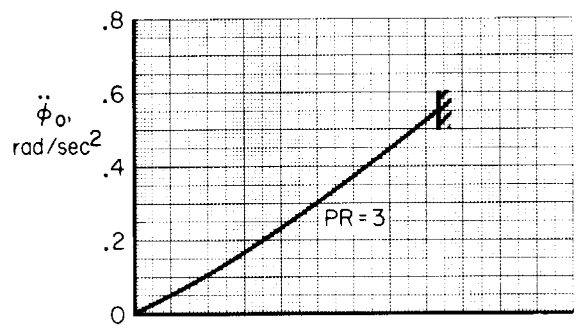
Control forces

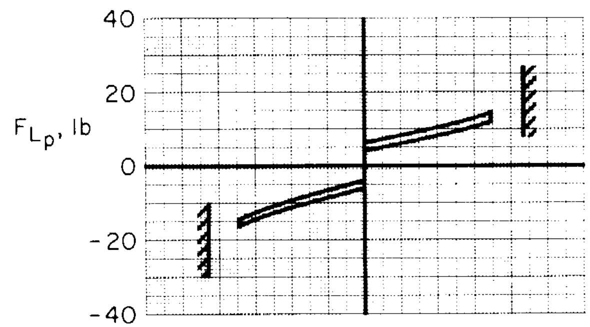
Comments



(e) CV-48, V = 60 knots, τ = 3.3, reference 12

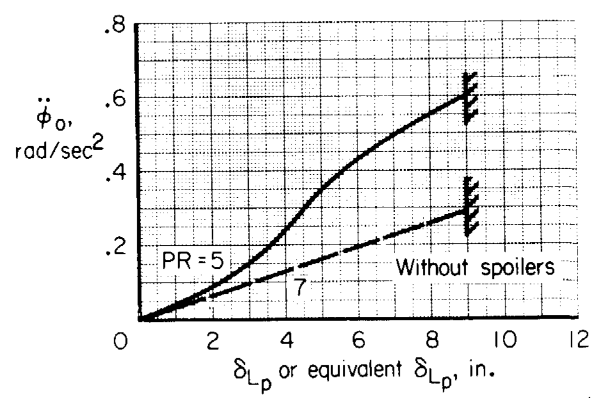
1. Stick control, satisfactory throw
2. Mechanical control system
3. Deficient due to high mass and inertia of spoilers
4. Aircraft response satisfactory, but damping a little low (PR = 4)

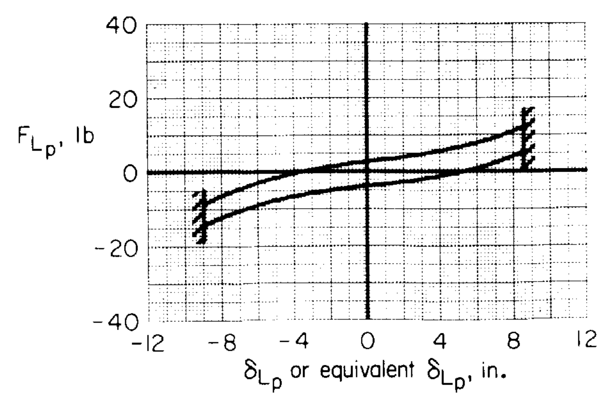




(f) 367-80, V = 85 knots, τ = 1.0, reference 14

1. Wheel deflection ± 75°, satisfactory
2. Fully powered system, evaluating pilot uses fly-by-wire system
3. Full control not useable because of potential damage to pods
4. Control forces satisfactory
5. Aircraft response satisfactory





(g) C-8A, V = 70 knots, τ = 0.8, unpublished data

1. Wheel deflection ± 80°, too large
2. Mechanical aileron control plus powered spoilers
3. Unsatisfactory non-linear response
4. Dangerously low control when only ailerons used
5. Control sensitivity too low at small control deflections
6. Aircraft easily disturbed in gusty air
7. Force characteristics unsatisfactory due to poor centering

Figure 26.- Concluded.

region frequently used in control of the aircraft. The large increase in force produced when the spoilers were engaged at about 10° wheel position and the rapid increase in response at 30° wheel position combined to produce unsatisfactory characteristics that masked the control-power ratings of this aircraft.

The CV-48 had satisfactory control power and sensitivity; however, the lateral damping being a little low created a tendency to overshoot a specified bank angle.

The 367-80 (fig. 26(f)) had more control power than could be utilized in any maneuvers performed. The roll acceleration at large control deflections was sufficiently high that for this large airplane there was some concern of possible structural damage. Initial low-speed tests of the 367-80 (ref. 15) were made with an aerodynamic tab control; the control was rated unsatisfactory by the pilot (PR-4-1/2) because of the high force gradient and nonlinearity. Installation of a powered control, with the forces shown in the figure provided a satisfactory control system. The control characteristics of the 367-80 at higher speeds are discussed in reference 25.

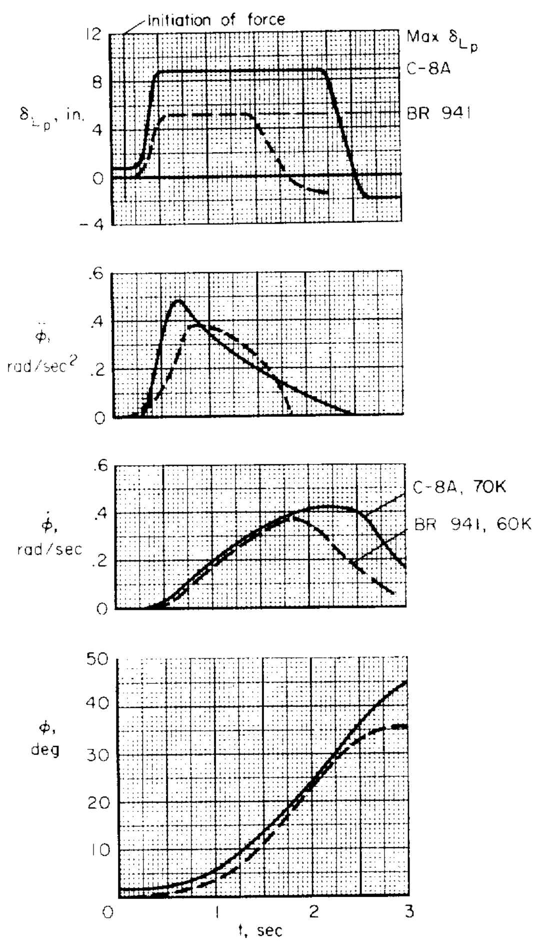


Figure 27.- Comparison of C-8A and BR-941 lateral response.

The lateral control characteristics of the C-8A were surprising. For the normal configuration of spoilers plus ailerons, the available control power was almost 50 percent greater than what was considered satisfactory on the BR 941 (tested at nearly the same speed and weight); yet the pilots rated the lateral control of the C-8A unsatisfactory (PR = 5). The turn-entry coordination of the C-8A was acceptable, the control friction was moderately high and the force gradient was low. The pilots commented that the sensitivity was lower than desired and expressed some dissatisfaction about the nonlinear relation of control power and wheel deflection. The C-8A was quite easily disturbed in turbulence, and occasionally the pilot required full lateral control to recover or compensate for gusts; hence, the pilot felt the need for additional control power. Because of these interesting characteristics, additional comparisons were made with the BR 941; the time histories of rapid full control input for the two aircraft are compared in figure 27. It is seen that the response to pilot control is quite similar and angular acceleration can be obtained rapidly for both aircraft. The C-8A has a higher angular acceleration capability, but this is compensated by a higher damping in roll so that there is a similar response. Several factors may contribute to the poor lateral-control rating of the C-8A. These are: high-aerodynamic damping, low-control sensitivity at small-control deflections, increased sensitivity at higher deflections, large control wheel deflections, moderately high control system friction, and poor centering characteristics.

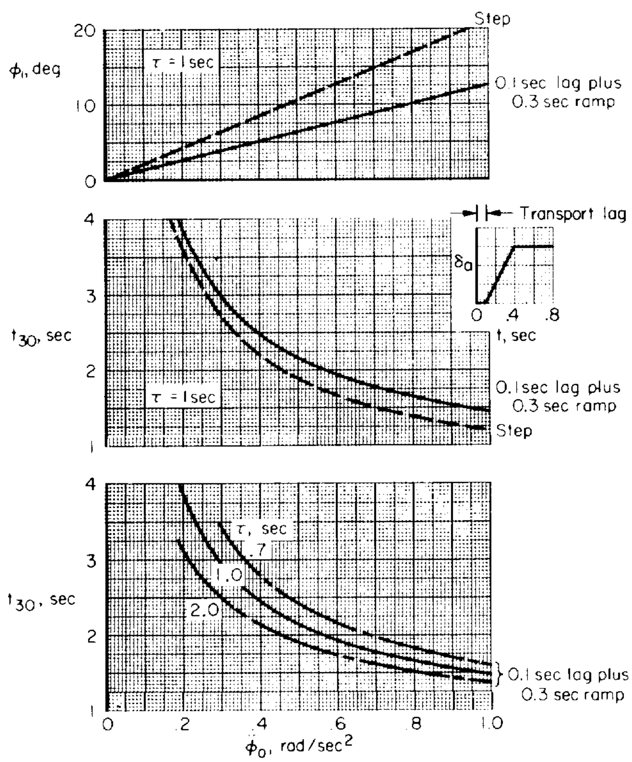


Figure 28.- Bank angle and time to bank.

The calculated relation between response and angular acceleration is given in figure 28 for several parameters. The top part of figure 28 relates the parameter of bank angle after 1 second, ϕ_1, to control power $\ddot{\phi}_0$, for a step and ramp input. The parameter, ϕ_1, has been used in V/STOL specifications (refs. 19 and 21), but it is difficult to obtain representative measurements and to correlate data because of the strong influence of control input shape and lags. The remainder of figure 28 relates the time to 30° bank angle (t_{30}) and control power. The parameter t_{30} was proposed as an indicator of control power in references 20 and 26 for conventional aircraft. Bank angles of about 30° were the maximum normally used during low-speed maneuvering of STOL aircraft. Data are insufficient for determining whether this parameter correlates; the values of t_{30} specified in the criteria were computed for the angular acceleration listed in the criteria, a lateral time constant of 1 sec, a transport lag of 0.1 sec (time between force application and control-surface movement), and a ramp input 0.3 sec long. The criterion of time to 30° bank angle can be easily measured and evaluated, and it includes the damping and control system characteristics. The criteria include a desired level of angular acceleration, even though this is redundant in some cases and more difficult to measure, to assure sufficient ability to counter gusts quickly.

The calculations relating response and angular acceleration are based on the following equations:

1. For step input

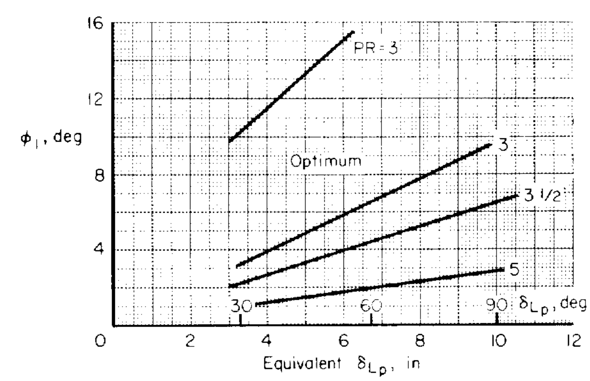
$$\frac{\phi}{\ddot{\phi}_0} = 57.3\left[\tau t + \tau^2\left(e^{-t/\tau} - 1\right)\right], \qquad \text{deg/rad/sec}^2$$

2. For ramp input

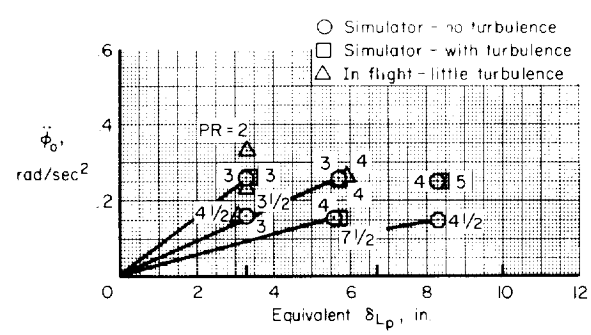
$$\frac{\phi}{\ddot{\phi}_0} = 57.3\left\{\tau t - \tau^2 - \frac{t_a \tau}{2} - \frac{\tau^3}{t_a}\left[e^{-t/\tau} - e^{(t_a/\tau)-(t/\tau)}\right]\right\}, \qquad \text{deg/rad/sec}^2$$

These equations are for a single degree of freedom. The transport lag must be included after the response is computed by these equations. Tests with STOL transports showed that a rapid lateral control input was approximated by a 0.1 sec transport lag and a ramp input 0.3 sec long; these time constants were used for the calculation of t_{30} and ϕ_1 given in table IV.

Lateral-control sensitivity.- Sensitivity was not varied systematically nor independently of control power on the STOL aircraft tested. In no case was there adverse comment about too high sensitivity near zero-control deflection; however, there were adverse comments about too low sensitivity and increased sensitivity with control deflection. Additional information on control sensitivity varied in a systematic manner is given in figure 29 for the 367-80 tested at 115 knots. Care must be exercised in using these data because of the higher test speeds and limited turbulence encountered. Figure 29(a) shows the importance of sensitivity; but also that a broad range can be utilized to obtain satisfactory handling. The lowest sensitivity for satisfactory handling at 115 knots was 0.04 rad/sec^2/in. control deflection. On examination, table IV indicates that this level of sensitivity was unsatisfactory for all STOL aircraft except the UF-XS. This aircraft, a seaplane, was not required to maneuver extensively and was equipped with attitude stabilization. Based on the other STOL aircraft a sensitivity of at least 0.1 rad/sec^2/in. is suggested for satisfactory handling at STOL speeds (table IV).



(a) Sensitivity; $1.03 \le \tau_R \le 1.42$ sec, little or no turbulence, flight and simulator



(b) Control power; $\tau_R = 1.1$

Figure 29.- Lateral control 367-80 (ref. 25), optimum force gradient; V = 115 knots.

The Breguet 941 had a nonlinear variation of angular acceleration with control deflection that gave higher control sensitivity at small lateral deflections than at large deflections (fig. 26(a)). This relation was satisfactory. The YC-134A and C-8A aircraft had low sensitivity at small deflections and greatly increased values at midlateral control deflection (figs. 26(d) and (g)); these characteristics were unsatisfactory because they caused overcontrolling.

The STOL transports with wheel-type controls had maximum wheel deflections that were too large. Reference 20 specified that the wheel deflections for conventional transports be limited to a maximum of ±60°. For STOL maneuvering the wheel motion must be compatible with one-hand operation. To compare the characteristics of aircraft having sticks and wheels, it was assumed that linear motion at the rim of the wheel was the pertinent factor. Thus a 60° wheel deflection corresponds to a stick deflection of about 7 inches, for an average wheel radius of 7 inches. The only STOL with a stick deflection this large was the VZ-3RY; for this aircraft, full lateral control could not be used because the stick contacted the pilot's knee.

Lateral control forces.- No systematic study was made at STOL speeds to relate control-system friction, force gradient, aerodynamic stability and control, and pilot opinion; however, based on the information presented in figure 26 and table III, some general comments can be made. First, the forces must be sufficiently low that one-hand control can be maintained easily over the entire control range; second, the friction must be low enough to permit good centering of the control; third, there must be harmony between the axes to avoid inadvertent control application.

The control-force criteria are stated merely as a maximum force to achieve the control-power requirement because there is insufficient information to prescribe levels of breakout force, friction, free play, lags, gradient, etc. The level of forces specified in the criteria are based on the tests of the STOL aircraft. Data from the 367-80 at 115 knots were included because it was tested with different force gradients. The fact that the criteria presented are insufficient is clearly demonstrated by a comparison of the force characteristics and pilot opinions of the 367-80 and C-8A aircraft (figs. 26(f) and (g)). The maximum forces for these two aircraft were similar and below the level specified for satisfactory operation; however, the C-8A control system was unsatisfactory because there were 6-lb of friction, 6-lb breakout, and a low gradient which caused poor centering and produced a spiral-type divergence. On the other hand, the 367-80 had a satisfactory system with the same maximum-force level, but it had 2 lb of friction, an 7-lb breakout force, and a 1.3 lb/in. gradient.

Lateral-control cross coupling.- For STOL aircraft with low-directional stability, high sideslip angles develop during maneuvering and the pilot cannot make precise heading changes, cannot accurately control sideslip during touchdown in crosswind landing, and in some cases is concerned about stalling the vertical fin. In addition, when the aircraft is disturbed at low airspeeds, small bank angles develop large yaw rates, and it is difficult for the pilot to maintain the desired heading. These problems of turn-entry coordination or cross coupling (or perhaps lack of cross coupling) will be illustrated first in figure 30 by the time history of a step-bank maneuver performed with the NC-130B at 70 knots (ref. 7). It can be seen that although the desired bank angle was obtained in 2-1/2 sec, 7 sec elapsed before the heading changed in the correct direction. During this time a large sideslip excursion occurred. The difficulty a pilot has in coordinating such a turn is shown in figure 31 by the different amounts and phasings of the rudder required to compensate for adverse yaw, yaw rate damping, and roll rate.

The degree of turn-entry coordination has been related to the ratio of peak sideslip excursion to the peak bank angle, $\Delta\beta/\Delta\phi$. The correlation of

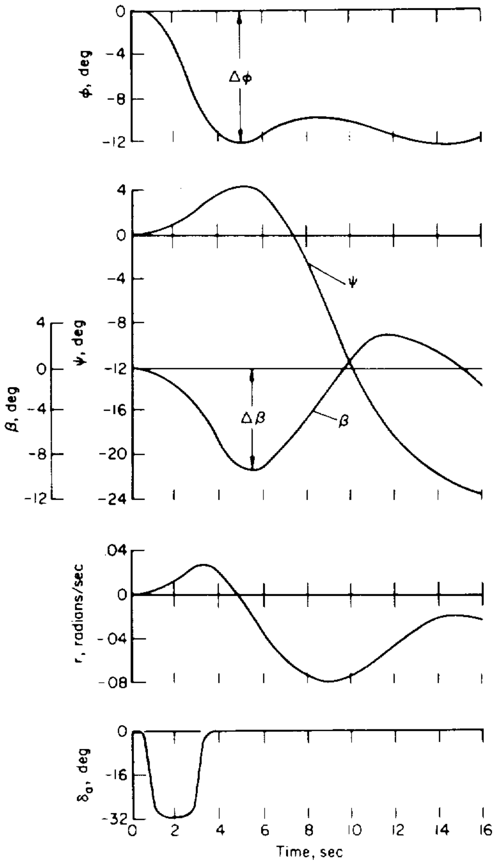


Figure 30.- Time history of the response of the NC-130B to a step bank maneuver; V = 70 knots (ref. 7).

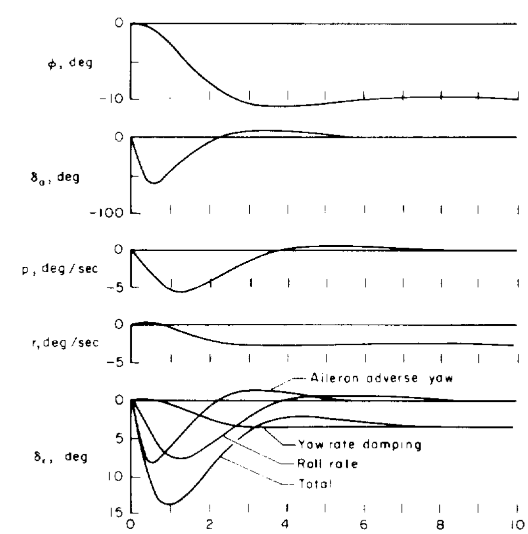


Figure 31.- Time history showing rudder requirements for a coordinated (β = 0) turn maneuver; V = 70 knots, NC-130B (ref. 7).

$\Delta\beta/\Delta\phi$ with pilot's opinion of turn coordination is presented in figure 32 for different aircraft and for a range of lateral-directional characteristics studied on the simulator. The $\Delta\beta/\Delta\phi$ is measured during a rapid bank-angle change with the rudder fixed as illustrated in figure 30. This maneuver is similar to that performed for a rapid heading change or a recovery from an upset. Figure 32 shows that when the value of $\Delta\beta/\Delta\phi$ was above 0.3, turn entry became a problem and the pilot gave an unsatisfactory rating (PR worse than 3-1/2). When $\Delta\beta/\Delta\phi$ was above 0.6, the aircraft handling became unacceptable for normal operation.

For the NC-130B turn entry presented in figure 30, the $\Delta\beta/\Delta\phi$ was 0.8 and the pilot rating was 6-1/2 in VFR and 7 to 8 in IFR. The parameter $\Delta\beta/\Delta\phi$ is generally not dependent on the magnitude of bank angle nor rapidity of control input. This parameter can be easily visualized and evaluated by the pilot when given a calibrated sideslip indicator.

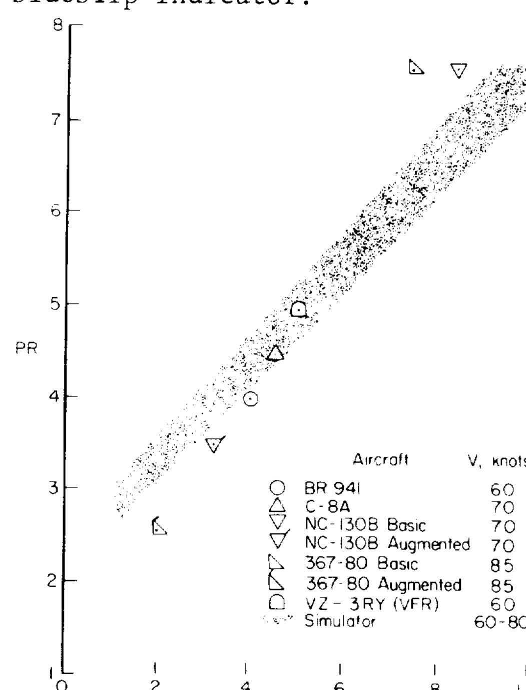


Figure 32.- Relation of turn entry coordination and pilot opinion in IFR.

Cross-coupling parameters such as N_p and $N_{\dot{\beta}}$ have been varied both in flight and on the simulator (refs. 7 and 11) to ascertain their effects on turn-entry coordination and to compare the $\Delta\beta/\Delta\phi$ with pilot opinion. The improvements in handling produced by positive N_p and $N_{\dot{\beta}}$ augmentation on the NC-130B and 367-80 aircraft are shown in figure 32. These improvements correlate with simulator results and show that $\Delta\beta/\Delta\phi$ is useful in assessing turn-entry coordination.

The coupling of the lateral control with longitudinal motion has been a smaller problem than turn-entry coordination. Some aircraft that used spoilers for lateral control have had minor lift-loss problems. The midspan spoilers of the C-8A aircraft produced an incremental normal acceleration of about -0.15 g at the center of gravity with full lateral control deflection; this acceleration was marginally acceptable. The BR-941 used outboard spoilers and less than -0.1 g was incurred with full lateral control, this acceleration was not troublesome and was considered satisfactory. None of the straight-winged STOL aircraft experienced any significant pitching moment when lateral control was applied. On the other hand, the pitching acceleration developed by lateral control on the early configuration of the swept-wing 367-80 flying at 85 knots was quite objectionable. The outboard spoiler panels, a major contributor to the pitching moment, were subsequently disconnected, and the pitching moment was essentially eliminated. The resulting loss in lateral control power was of little consequence because there was more control than necessary. Quantitative values of acceptable pitching motion are not available.

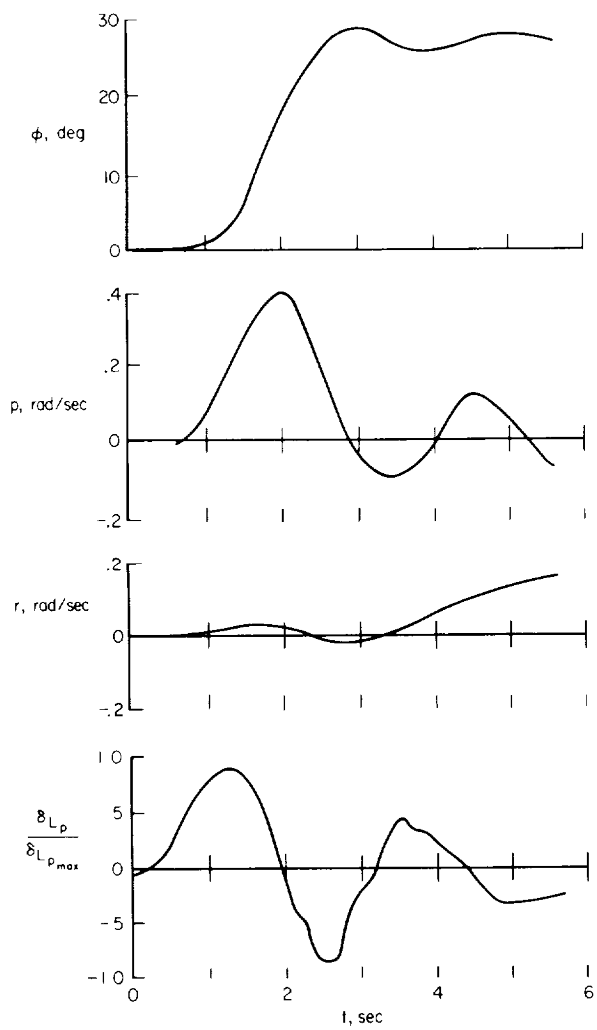


Figure 33.- Example of step bank with low apparent damping; V = 60 knots, rudder fixed.

Apparent roll damping.- The roll damping of all STOL aircraft was satisfactory or at least acceptable (pilot rating of 4 or better). Specific levels of roll-time constant are presented in a later section on stability and damping. Apparent roll damping is included in the aircraft response to control criteria because the pilot has difficulty isolating control-system lags when evaluating damping during lateral-control maneuvers.

An illustration of a time history of a step bank for a STOL with low roll damping is presented in figure 33. To maneuver quickly the aircraft is rapidly banked from level flight to 30° using a large control deflection. In order to stop the roll rate at the desired bank angle the pilot applied opposite control of a magnitude as large as the input. More than two of these reversals were needed to stabilize near 30° bank. This control activity was considered unsatisfactory (PR = 4), see reference 10.

Directional control power.- The significance of low airspeed during crosswind approaches is illustrated in figure 34. At low airspeeds the crab or sideslip angle required to track the runway centerline is considerably greater than the pilot is normally used to. For some of the STOL aircraft evaluated during moderate crosswinds, it was easier to use the sideslip or wings-down method because the amount of bank angle required to balance the aircraft was small, and it was not necessary to decrab the airplane through a large heading angle just prior to touchdown. The maximum sideslip capability of the aircraft evaluated is included in the figure, and it can be seen that none of the aircraft could be considered for operation with crosswind components in excess of 25 knots. Since it is possible that these sidelip angles might be limited by proximity to stalling the vertical tail, it can be realized that the crosswind requirement for STOL aircraft is an important design consideration. It will be difficult to design STOL aircraft to operate safely in crosswinds that are over 40 percent of the approach speed. Therefore, the steady-state directional control criteria are given quantitatively only for the minimum level of safe operation.

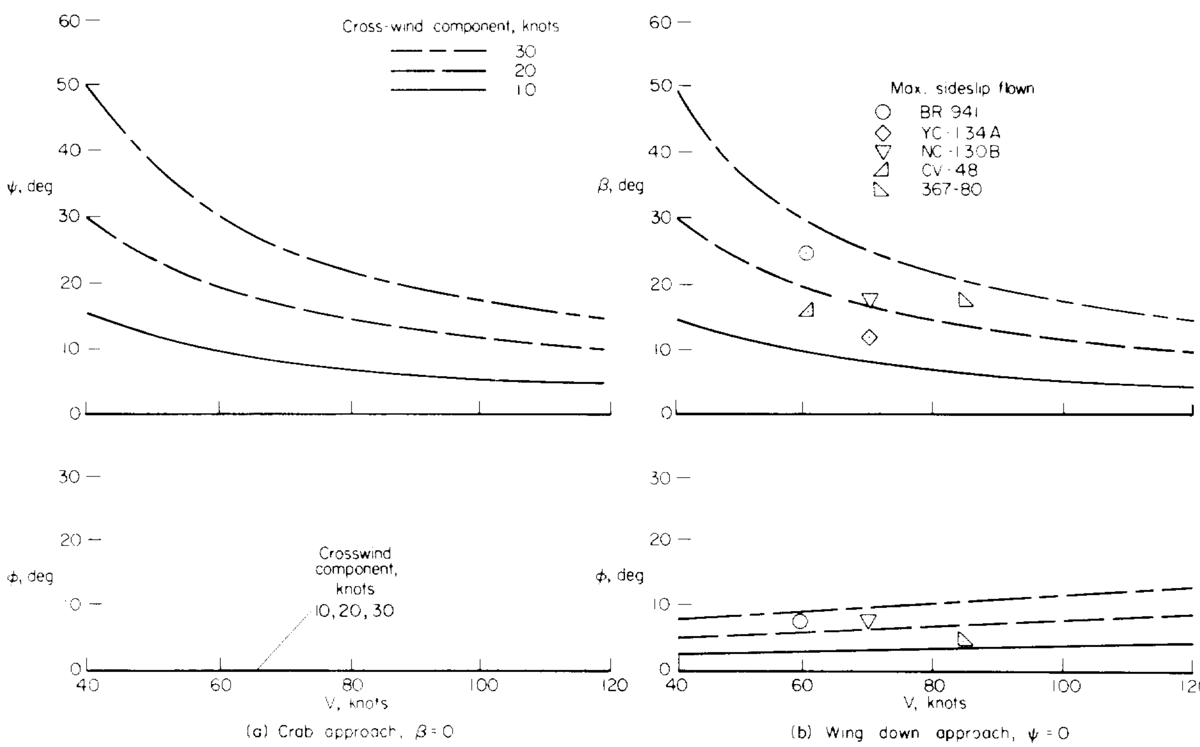


Figure 34.- Effect of airspeed on cross-wind approaches.

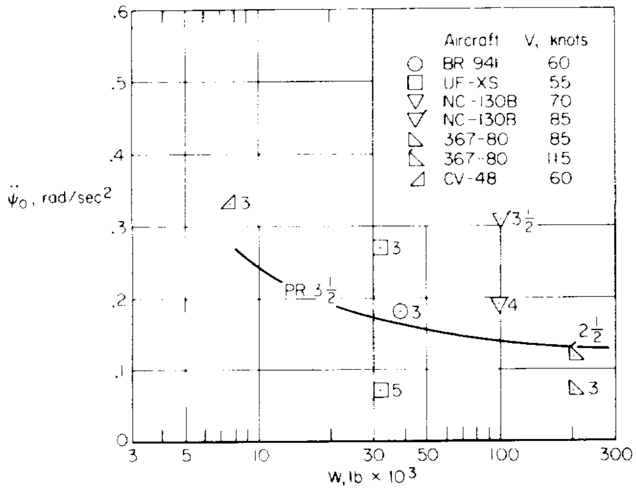


Figure 35.- Directional response. Pilot rating next to symbol.

To rapidly decrab the aircraft, or to quickly reduce unwanted sideslip angles that occur during maneuvering, angular response to rudder pedal deflection is also desired. Figure 35 gives the available control power measured for the different STOL aircraft and the pilot ratings based on the ability to maneuver the aircraft with all of the powerplants operating. It was concluded that the time to change heading 15° was a reasonable task. The times listed in the criteria were computed for a 0.3-sec ramp control input with angular accelerations of 0.16 and 0.08 rad/sec^2 and a damping time constant of 4 sec using the same equations as for the lateral response described earlier. For STOL aircraft without interconnected propulsion systems large asymmetric yawing moments occurred with an engine failure; in some cases, the asymmetric rolling moment of powered-lift aircraft was more critical (refs. 4, 5, and 12).

Directional control forces.- There were only a few comments on the directional force characteristics of the STOL aircraft. The UF-XS was the only STOL aircraft for which the pilot noted that the force gradient was too low, and this information was used to develop a minimum force level for the criteria.

Directional control cross coupling.- The most prevalent cross coupling from directional control input is the lateral response or dihedral effect. It is generally agreed that dihedral effect in moderate amounts is a desirable feature. Figure 36 presents the steady-state sideslip characteristics of

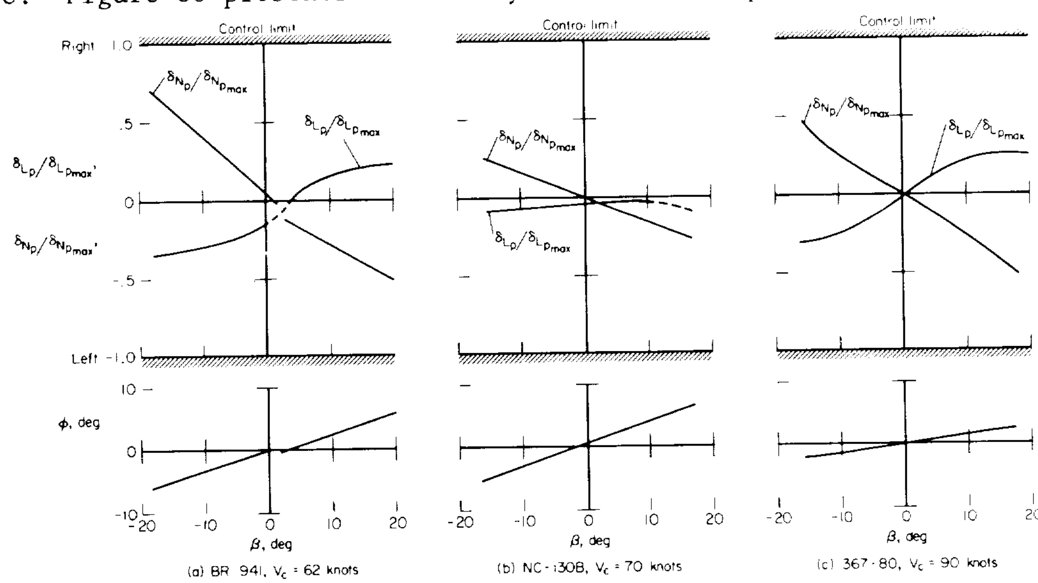


Figure 36.- Steady-state sideslip characteristics.

several STOL aircraft. These airplanes required little lateral control in steady sideslip, and this lack of dihedral effect was not considered a deficiency. References 11 and 14 have indicated that negative dihedral effect is highly undesirable and can produce a spiral instability. On the other hand, too much positive dihedral effect creates undesirable lateral-directional oscillations, and this will be discussed in a later section. For the purpose of this directional control section, however, the concern is that sufficient lateral control power be available at the maximum sideslip angle specified to insure adequate control of bank angle.

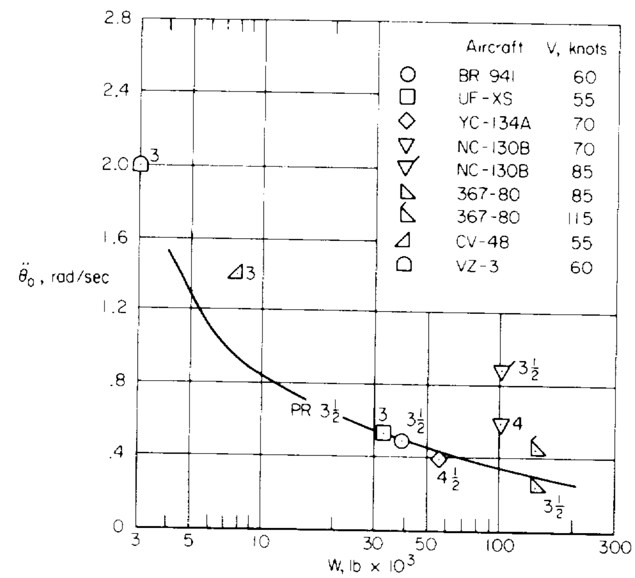


Figure 37.- Pitching acceleration. Pilot rating next to symbol.

Longitudinal control power.- The available nose-up longitudinal control power and rating are presented in figure 37 for the different STOL aircraft in the approach, landing, and take-off speed range for one center of gravity. For the CV-48 and BR 941 full nose-up control was used at the lift-off speed for the best take-off performance. Figure 22 showed that a 10° attitude change was quickly made, and the pilot reported that the maneuver was simple to perform (ref. 10). For the BR-941 half of the nose-up control was used to flare the aircraft from the steeper approach angles (refs. 9 and 10); this attitude change was required to develop sufficient normal acceleration by lift increases, and also to produce the proper fuselage attitude at touchdown. For the 367-80 the trim required in ground effect at 85 knots reduced the angular acceleration from the value shown to an inadequate value which was rated 4. For this larger aircraft large negative normal accelerations occurred at rearward "passenger locations" when large control steps were made at altitude. From these tests it would be inferred that in order to maintain passenger comfort, the angular acceleration would have to be restricted on the larger aircraft and greater emphasis would be placed on developing normal acceleration by other means, such as power or direct-lift control.

Little longitudinal control was needed during the approach because flight path was controlled primarily by modulating engine power, and moderate angle-of-attack excursions produced by atmospheric disturbances could be corrected by small longitudinal control inputs.

The longitudinal control system must also be capable of trimming the aircraft throughout the flight envelope. Figure 38 gives the variation of elevator angle with angle of attack for two STOL aircraft. Because of the low static stability and high control effectiveness, little control is required to trim over the angle of attack and power range in the approach and landing configuration. (The trim changes that occur with power application will be discussed in the next section.) All aircraft had sufficient nose-down pitching response at the minimum speed to effect a satisfactory recovery. No criteria for this latter requirement can be given other than to state that the longitudinal control must be capable of developing a nose-down pitching velocity at the minimum speed under all power conditions. Care must be taken when attitude stabilization systems are included in the control so that the pilot will be given proper information to recognize the amount of control remaining at high angles of attack when low stability is augmented. Some of the STOL aircraft were also tested over their allowable center-of-gravity range, and no significant trim problems occurred. In the case of the BR 941 at the forward center of gravity the rotation rate was reduced at nose wheel lift-off speed; however, the take-off performance was not noticeably affected.

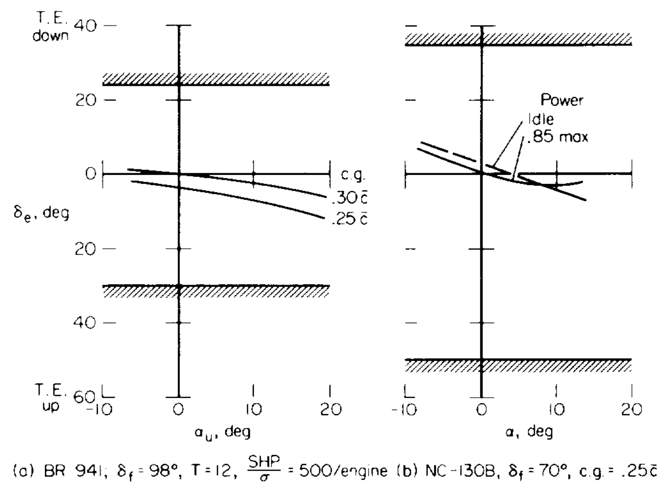


Figure 38.- Examples of longitudinal control required for trim.

To assure acceptable control near the ground to properly adjust touchdown attitude, to avoid porpoising, and to compensate for ground effect, it is proposed that the longitudinal control be sufficient to trim the aircraft to the landing attitude in ground effect at a speed corresponding to the approach reference criteria minus 5 knots.

The response and damping of all the STOL aircraft were rated 4-1/2 or better, and therefore it was not possible to specify criteria for a lower, acceptable level of control power.

Longitudinal control sensitivity, forces, linearity, and apparent damping.- The requirements for these characteristics are comparable to those for lateral control. Although it is noted that harmony between lateral and longitudinal control should exist, no related criteria are presented.

Flight-path control.- There are three general flight areas in which the throttle can be used for flight-path control: one, tracking of the flight path during the approach and preliminary portion of the landing; two, control of sink rate at touchdown; and, three, making gross changes to flight path such as for wave off and turning flight. Criteria are presented separately for each of these areas.

In the tests of reference 10, the engine response to modest throttle changes corresponded to a lag of about 0.5 sec plus a first-order time constant of about 0.7 sec, and there was little lag between normal acceleration and power changes. It was noted in these tests that an incremental normal acceleration of more than ±0.1 g could be obtained by throttle application. This response was acceptable for tracking the flight path during the approach down to about 50 ft provided that little pitching acceleration was produced by power. The pilot felt that larger engine lags and time constants would have reduced the ability to track the ILS glide slope. This response was too long to arrest the sink rate at touchdown, however. None of the STOL transports were flared by increasing power because the engine response was too slow to develop the desired normal acceleration for flaring, and the aircraft also had to be rotated for proper ground attitude. Therefore the normal acceleration required for flaring was developed by rapidly increasing the aircraft attitude which increased the angle of attack. Reference 27 noted that a time constant of less than 0.5 sec and a thrust-weight ratio of 1.09 (approximately an incremental normal acceleration of 0.09 g) was needed for satisfactory control of touchdown for V/STOL vehicles. It is felt that these values are also desired for STOL operation if power is used to flare. The response for gross changes to the flight path are the least stringent in terms of engine response characteristics. In the tests of reference 9, 2 sec were required to achieve wave-off power. This delay was satisfactory provided the pitching moment produced by power was small. Without a throttle-elevator interconnect, the pitchdown acceleration of this deflected-slipstream configuration negated the incremental normal acceleration even though the corresponding trim required was a small part of the available longitudinal control power (see ref. 9). References 11 and 13 gave simulator results of studies that include the effects of cross coupling between pitching moment and power.

No data on desirable throttle characteristics were obtained for these STOL aircraft.

Aircraft Response to External Disturbances

The purpose of this section is to specify levels of stability and damping that will limit the excursions of the aircraft when disturbed from trimmed conditions and that will limit the time and effort required by the pilot to correct these disturbances. Some of the aspects of stability and damping, such as cross-coupling and apparent damping, were included in the section entitled "Criteria for Aircraft Response to Control Input"; however, even when these effects are minimized, the response of the aircraft to external disturbances must be considered.

Lateral-directional stability and damping criteria.- The following table presents the proposed criteria for aircraft response to disturbances at STOL speeds.

Item	Parameter to be measured	Level for satisfactory operation	Level for safe operation
1. Directional stability	Period of oscillation	Less than 12 sec	Insufficient data
2. Directional damping	Time to half amplitude	Less than 8 sec	Must be positive
3. Dihedral effect	No criteria, insufficient information	- - -	- - -
4. Spiral stability	Time to double amplitude	Not less than 20 sec	Not less than 5 sec
5. Lateral damping	Roll time constant	Less than 2 sec	Less than 4 sec

Directional-stability and damping substantiation. The directional-stability and damping characteristics of several STOL aircraft are given in figure 39. The left-hand figure shows that there is no correlation between pilot opinion and directional frequency. For these aircraft the behavior was dominated by the damping and cross coupling associated with low stability (low directional frequency). When adequate damping and satisfactory turn coordination were provided, as on the augmented 367-80 and NC-130B and in simulator tests, the lowest directional frequencies tested were acceptable. These tests indicated, however, that lower directional frequencies might not be acceptable because the static directional stability would be too low.

The right-hand portion of figure 39 relates pilot opinion and the Dutch-roll damping parameter, $\xi\omega_d$, for the STOL aircraft with a directional frequency range of 0.5 to 1.2 rad/sec. For damping ratios less 0.3, $\xi\omega_d$ is approximately inversely proportional to time to half or double the amplitude of the Dutch-roll oscillation. In general, the ratings improve as the damping is increased; however, the turn coordination also influences the ratings to a considerable degree, as indicated by the less favorable ratings shown in the right-hand figure for $\Delta\beta/\Delta\phi$ of 0.6 compared to those for $\Delta\beta/\Delta\phi$ of 0.3. Another factor is the method of providing damping at the low frequencies. For example, when the directional damping of the NC-130B was augmented by a signal proportional to yaw rate, the damping of the directional oscillation was improved; however, the pilot rating was not changed because a large sideslip angle was incurred in steady turns which the pilot considered unsatisfactory (ref. 7). When damping was augmented with sideslip rate damping, a significant improvement in damping as well as turn-entry coordination occurred. The atmospheric conditions had a strong bearing on the test results; when the sideslip rate damping was based on wind information (i.e., differentiation of a sideslip vane), the aircraft was unsatisfactorily disturbed in turbulent conditions whereas when the damper was based on a flight-path sensor the results obtained were satisfactory. Satisfactory ratings for the 367-80 at 85 knots were obtained only when both sideslip rate damping and satisfactory turn entry characteristics were provided with an augmentation system.

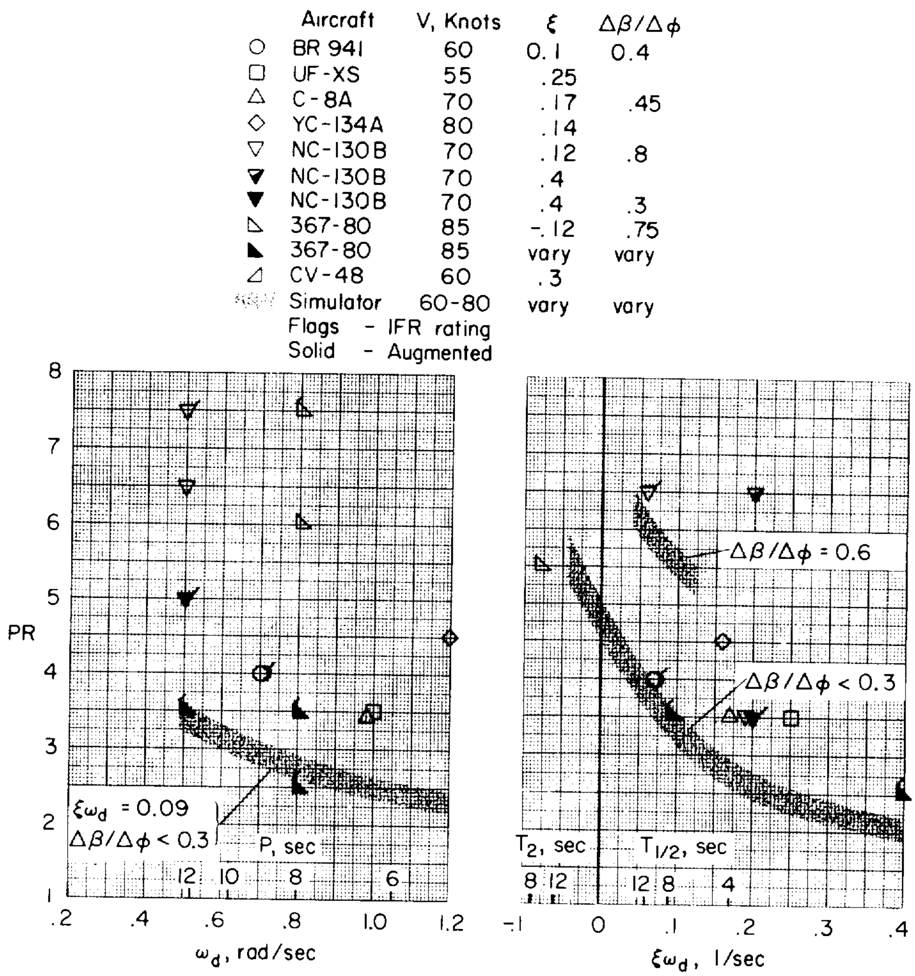


Figure 39.- Pilot opinion of directional frequency and damping for several STOL aircraft.

The effect of poor directional characteristics is more pronounced during IFR approaches than VFR because the pilot requires more precise control of heading. For the basic NC-130B the IFR task became impossible and was rated 7-8 as compared to 6-1/2 for VFR; in contrast, the Breguet 941 was rated 4 for both VFR and IFR.

It is concluded that STOL aircraft will be unsafe if the directional oscillation is undamped or divergent, and that this oscillation must be damped to 1/2 amplitude in less than 8 seconds to be satisfactory (PR = 3-1/2). However, this criterion is not sufficient by itself; the aircraft must also comply with other criteria such as those presented for satisfactory cross coupling before safe and/or satisfactory directional stability and damping characteristics can be assured.

Dihedral effect.- The dihedral effect on the different straight-wing STOL aircraft did not cause problems at STOL speeds, but on the swept-wing 367-80 it produced a divergent Dutch-roll oscillation which caused the low directional damping of the basic airplane.

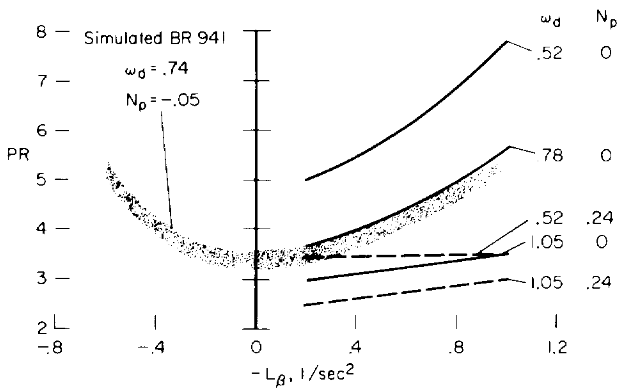


Figure 40.- Effect of dihedral on pilot rating.

Figure 40 shows the variation of pilot rating with the parameter $-L_\beta$, for two values of N_p and three values of directional stability, ω_d, obtained with the 367-80 (ref. 14); also included are results from the simulation of the Breguet 941 (ref. 11) where N_p was small. When N_p is low or negative (as is generally the case for unaugmented aircraft), near zero L_β is preferred to keep the sideslip angle small while the aircraft is being maneuvered; when optimum N_p is provided, the pilot is more tolerant of L_β because the N_p coordinates the turn (refs. 11 and 14). In turbulence at STOL airspeeds, reduced dihedral effect was preferred because it reduced the rolling disturbances produced by sideslip angles from the gusts. On the other hand, reduced dihedral effect, can produce spiral instability when roll due to yaw rate, L_r, is present (ref. 11).

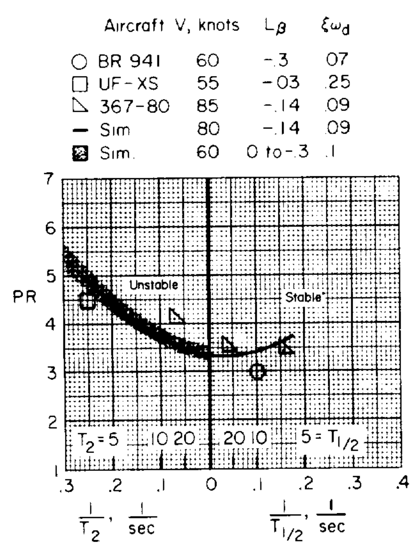


Figure 41.- Variation of pilot rating with spiral stability.

<u>Spiral stability</u>.- The effect of spiral stability on pilot opinion is shown in figure 41 where simulator results as well as some flight results are given for the 367-80 and Breguet 941. The spiral stability is shown in terms of the reciprocal of time to half amplitude (stable) or of reciprocal of time to double amplitude (unstable or divergent). For the tests with the 367-80, a slightly stable condition ($T_{1/2}$ = 20 sec) was considered optimum; increased stability was objectionable because of the necessity of holding lateral control in a steady turn. Satisfactory handling in STOL approaches can be attained with spiral instability, provided the bank angle does not double in less than 20 sec. If the bank angle doubles in less than 5 sec, these characteristics may be unsafe, particularly in IFR operation.

In addition to the previous requirement another factor, inability to trim, must be considered. This characteristic is difficult to separate from spiral stability. The spiral stability could be evaluated on the aircraft used for figure 41 because they all had lateral control systems with good mechanical characteristics. On the other hand, aircraft with poor wheel centering, such as the C-8A, could not be trimmed laterally; consequently, the "aerodynamic" spiral mode was masked. When the C-8A was laterally disturbed and the control was returned to the *position* for trimmed wing-level flight, the bank angle doubled in 10 sec, and this spiral instability would have been acceptable. However, when the control was *released* rather than returned to the correct position, a large rolling moment remained. This moment produced an average 20° increase in bank angle in 5 sec, and was unacceptable for IFR operation. At the present time, no criterion has been developed that provides for such inability to trim in the spiral mode; however, it is believed desirable to limit the bank angle or roll rate that would occur after the control is pulsed and released.

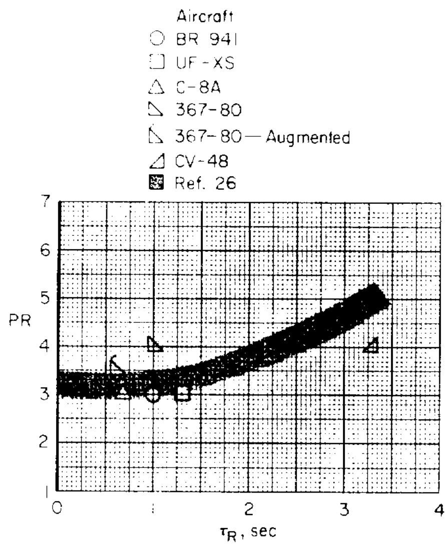


Figure 42.- Roll time constant.

Lateral damping.- Figure 42 compares the ratings and time constants for the different STOL aircraft with information from reference 26. The roll time constants for the STOL aircraft tested ranged from 0.6 to 3.3 sec (table IV). The CV-48 with the 3.3-sec time constant was rated as having too low damping (PR = 4). The remaining aircraft had time constants less than 1.3 sec, and these were satisfactory. Additional information on roll damping was presented in references 26 and 28. Reference 28 suggested that the roll time constant for transport aircraft should not exceed 2 to 3 sec for satisfactory rating; whereas, reference 26 suggested that 1.3 sec be the maximum. Based on the current STOL information, the criterion of a maximum roll time constant of 2 sec is suggested for satisfactory handling of STOL aircraft at low speeds.

Not only should there be a criterion for maximum roll time constant, but there should probably be a minimum value to prevent excessive disturbance by gusts. An unaugmented aircraft with a small roll time constant, T_R, has high aerodynamic roll damping, $-L_p$. This aerodynamic damping is produced by high section lift curve slopes which in turn increase the sensitivity of the aircraft to gusts. Consequently, low damping is desired to avoid being disturbed in turbulent air. This presents a conflicting requirement because the pilot desires good damping to lateral control inputs. An example was the C-8A which had a low roll time constant; the pilot rated the damping good, as noted in figure 42, but stated that the aircraft was quite disturbed by gusts. On the other hand, the augmented 367-80 with the same low time constants, but half provided artificially, was less disturbed by gusts and had good damping to roll control. Unfortunately, there is no easy method of evaluating an aircraft in a controlled gust environment in order to develop appropriate criteria. Consequently, considerable operational experience is required to evaluate gust sensitivity. The data in figure 42 were primarily from the pilot's evaluation of damping of aircraft motion to his lateral control input; therefore the ratings are not necessarily a measure of the aircraft's sensitivity to gusts.

Longitudinal stability and damping.- Insufficient information is available to formulate desired levels of longitudinal stability or a criteria to evaluate the stability; however, the level of static stability should not be so low that the resulting short period motion is aperiodically divergent.

The static and dynamic longitudinal stability levels for the different STOL aircraft have been quite low. Nevertheless, the longitudinal handling was acceptable to satisfactory because the short period mode was usually critically damped and moderate angle of attack excursions could be permitted without large changes in normal acceleration, airspeed, and flight path (refs. 9-11). Figure 43 presents the boundaries of stability and damping developed in the variable stability helicopter tests of reference 29. Included in this figure are static stability and damping values measured for several STOL aircraft. The short period frequency could not be accurately measured in flight because the frequency was low (ω < 1-1/2 rad/sec), the damping was high (ξ > 1), and the control power was high. This figure shows that satisfactory handling could be obtained with near zero M_α, provided adequate damping was present.

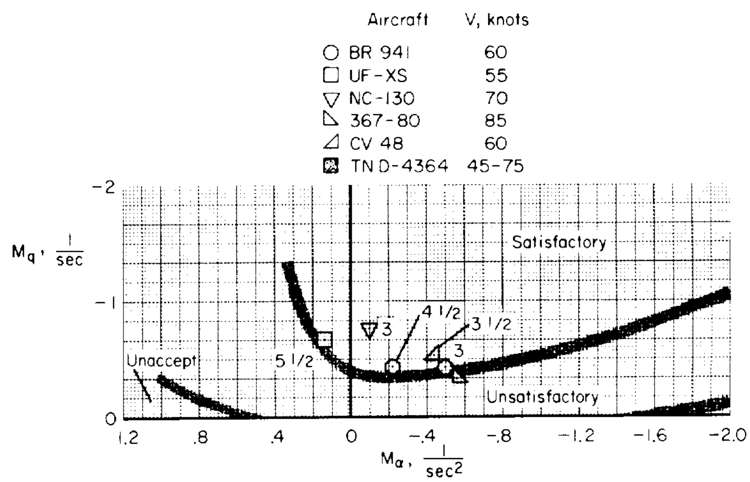


Figure 43.- Angle-of-attack stability and pitch rate damping. Pilot rating next to symbol.

Reference 10, tests of the BR 941, pointed out that pilot opinion improved significantly when the center of gravity was forward rather than aft, even though the dynamic motion was not greatly different. The corresponding increase in M_α, shown in figure 43, reduced the pilot effort to maintain the desired angle of attack in smooth air under VFR and IFR conditions. Experience in rough air is insufficient to determine the effects of M_α. However, it would be expected that high levels of M_α are not desired because of the rough ride; for such an environment, attitude stability through augmentation would be preferable to angle-of-attack stability. Reference 29 showed that changes in positive speed stability, M_V, had only a minor effect on the pilot rating. It was noted in references 11 and 13 that speed stability was related to the pitching moment produced by a thrust change; the benefits of speed stability were much less noticeable to the pilot than the corresponding adverse trim caused by a thrust change.

For most of the STOL aircraft, the phugoid motion was of low frequency (periods greater than 20 sec) with near neutral damping and caused no problem; in fact, it was usually difficult for the pilot to excite this motion. For one configuration the phugoid had a period of 12 sec with divergent damping (ξ about -0.15). This caused no problem in VFR flight, but the pilot anticipated problems in routine IFR operations.

Conclusions

STOL aircraft generally had low levels of stability which were satisfactory provided the damping was sufficient and the mechanical and aerodynamic control characteristics were good. It is necessary to have low friction, force gradients, and control centering consistent with one-hand operation; in addition, lags and adverse cross coupling should be minimized. Criteria for control and stability are presented for two levels; one, which is the minimum for satisfactory handling, and the other which is acceptable, but requires considerable pilot workload. In addition, substantiating data are presented that relate pilot opinion and pertinent stability and control characteristics.

The lateral control requirement was dictated by rapid correction to disturbance by gusts; good turn-entry coordination and damping was necessary for precise maneuvering. The directional control was primarily determined by the necessity for trimming in crosswinds. None of the STOL aircraft could be trimmed in crosswinds exceeding 40 percent of the approach speed. Longitudinal control was dominated by either trim or maneuvering.

There are conflicting requirements for lateral-directional stability and damping. Low directional stability is desired to reduce the disturbance of the aircraft by gusts; however, low stability increases problems of turn-entry coordination and of maintaining heading. Similarly, high directional damping is desired, but the aircraft becomes sluggish to control. High lateral damping can cause the aircraft to be more disturbed by gusts. Slight spiral instability could be tolerated, but a slight spiral stability was optimum. Low dihedral effect was desired provided it did not cause spiral instability.

The static and dynamic levels of longitudinal stability for the STOL aircraft were quite low, but these levels were acceptable because they were usually critically damped. Information was insufficient for presenting criteria.

The conflicting requirements of low stability and damping to reduce aircraft disturbance by gusts and of good stability and damping to maintain the desired flight path will be best satisfied by augmenting stability and damping about the flight path axes rather than about the wind axes.

CONCLUDING REMARKS

This report summarizes previously reported NASA flight and simulator data on STOL aircraft, vehicles that derive a large portion of their lift and control from the propulsion system. Data are extracted and presented in a form that should be useful for the designer and operator in evaluating new designs and for regulatory agencies for ascertaining the airworthiness of commercial STOL transport aircraft. The main emphasis has been to provide information for satisfactory performance, operational characteristics, and handling qualities during approach and landing, because these characteristics are required to provide safe and consistent operation during routine flying in a wide variety of weather conditions. The data are primarily addressed to

STOL aircraft operating at 40 to 80 knots, with descent and ascent angles of 6° and greater, multiengines, and gross weights from 30,000 to 100,000 lb.

It is concluded that STOL aircraft utilizing power to develop lift can safely operate with smaller speed margins than conventional aircraft. The speeds chosen cannot be singularly related to the stall speed by some factor such as 1.3 times the power-off stall speed. A method is given whereby an operating envelope can be developed to estimate a safe operating speed considering maneuvering margins, operating restrictions, and powerplant failure. The margins and restrictions required are discussed, and illustrative examples are given.

At present, rational field length factors cannot be developed because flight data are insufficient for assessing consistency in STOL performance over a range of runway and atmospheric conditions. It is recommended that performance measurements be made with restraints imposed to simulate the operational environment and to expose adverse handling. With such a method, rational field lengths can be ascertained for each STOL aircraft. Field length factors will have to be developed for different types of STOL aircraft to account for their unique characteristics and operational techniques.

Handling qualities criteria for different parameters are presented for two levels: one that should provide satisfactory handling under a wide operating environment including IFR; and the other, the lowest level of an individual parameter that can be tolerated in some task, but would still provide a satisfactory rating for the overall landing task. It is concluded that with the generally low level of stability and damping present on STOL aircraft, the mechanical control characteristics assume a larger importance in overall handling than they do in conventional aircraft. The control friction, gradients, harmony, sensitivity, lags, etc., are as important as the basic stability and damping of the aircraft. In fact, in most cases, these are indistinguishable by the pilot and must be included in evaluating aircraft stability and control. Insufficient systematic work has been done to define acceptable mechanical control characteristics for STOL craft; however, some preliminary guidelines are given. It is concluded that conventional stability and damping present conflicting requirements with handling in gusty environment. That is to say, that high levels of aerodynamic stability and damping at STOL speeds are not necessarily desired because they cause the aircraft to be more disturbed in gusty air. Consequently, augmentation with respect to the flight path will be more desirable than augmentation of conventional aerodynamic parameters.

It should be noted that the proposed methods, margins, and criteria presented are a first cut and will require further verification in a systematic manner with different types of STOL aircraft. Like other flying qualities specifications, requirements, and standards, the recommended levels of margins and criteria will have to be reviewed and revised as more experience is gained.

Additional research must be performed to define the gust, wind shear, and crosswinds that are encountered in STOL operation. Statistical data are needed to determine the effect of these environmental conditions on performance margins, field length factors, and obstacle clearance angle. The effects of gusts and wind shear on handling qualities must be evaluated further. A systematic study should be made to relate control system characteristics (friction, gradient, harmony, lags, etc.) to control power, control sensitivity, stability and damping in IFR conditions with representative turbulence levels. It is necessary to define the desired levels of longitudinal stability and damping in relation to flight-path tasks when power is used for control. Tests should be made to determine how attitude stabilization about the lateral and longitudinal axes affects the handling qualities and the control power requirements. More flight experience is needed to define methods of efficiently operating STOL aircraft under IFR in the terminal area and to define the guidance and displays needed.

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National Aeronautics and Space Administration
Moffett Field, Calif., 94035, June 19, 1969

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TABLE I.- GEOMETRY OF STOL AIRCRAFT

Aircraft	VZ-3RY	CV-48	UF-XS	C-8A	BR-941	YC-134A	NC-130B	367-80
W, lb	2,900	7,730	32,000	34,000	38,500	55,500	100,000	150,000
I_{xx}, slug ft^2	1,440	6,500	184,000	273,000[a]	225,000	320,000	2,000,000	2,570,000
I_{yy}, slug ft^2	2,570	6,000	173,500	215,000[a]	140,000	225,000	900,000	2,250,000
I_{zz}, slug ft^2	3,450	12,300	329,000	447,000[a]	400,000	520,000	2,800,000	4,730,000
S, ft^2	125	193	835	945	889	1,235	1,745	2,821
b, ft	23.4	30.9	80	96.0	76.1	110.0	132.7	130
$\bar{c}$, ft	5.3	7.9	10.75	10.29	12.15	11.66	13.71	20.0
Trailing-edge flap	Full-span double slotted	Double-hinge slotted	BLC flap	Full-span double slotted	Full-span triple slotted	BLC flap	BLC flap	BLC flap
Trailing-edge flap deflection, deg	40	90	55	62	98	60	70	85
Leading-edge device	Full-span slat	Part-span Krueger flap	Full-span slat	Increased camber	Increased camber	None	None	Full-span slats and Krueger flaps
Reference	8, 13	12	11	---	9, 10	4	5, 6, 7	14, 15

[a]at 38,000 lb

TABLE II.- SUMMARY OF APPROACH SPEEDS AND MARGINS

Aircraft	γ, deg	V_{min}, knots	α_{max}, deg	Limited by	V_a	α	Limited by	$\frac{V_a}{V_{min}}$	ΔV, knots	$\Delta\alpha$, deg	Approach reference
YC-134A	-1	64	10	Stall	75	-1	Objectionable stability and control	1.17	11	11	Indicated angle of attack
	-4	68	10	↓	78	0	Proximity to stall	1.15	10	10	Indicated angle of attack
	-9	77-1/2	9	↓	96-1/2	-3	Flare capability	1.24	19	12	Airspeed
NC-130B	-1	55[a]	12	Stall	63	4		1.15	8	8	Angle of attack
	-2	[a]56-1/2	12	↓	65	3		1.15	10	9	↓
	-4-1/2	[a]61-1/2	11	↓	70	2		1.14	9	9	↓
	-8	68[a]	8	↓	81	-1	Flare capability	1.20	13	9	↓
VZ-3RY	-16	36		Lateral control	40		Proximity to V_{min}	1.11	4		Airspeed and power
UF-XS	-3-1/2		20[b]	Stall	50	12[b]	Proximity to V_{min}			8	Airspeed and rate of descent
	-5		18[b]	↓	55	10[b]	↓			8	↓
CV-48	-6	47	33[b]	Stall	55	10[b]	Proximity to V_{min}	1.17	8	23[b]	Airspeed and rate of descent
	-7-1/2	51	28[b]	↓	60	12[b]	↓	1.18	9	16[b]	↓
BR-941	-4	49	20[b]	V_{min}	57	3[b]	Proximity to V_{min}	1.16	8	17[b]	Angle of attack
	-5	50	20[b]	↓	57-1/2	3[b]		1.15	8	17[b]	↓
	-6	52	18[b]	↓	59	3[b]		1.14	7	15[b]	↓
	-7-1/2	53	17[b]	↓	60	3[b]		1.13	7	14[b]	↓
C-8A	-7	60	10	Stall	70	1	Ability to flare	1.17	10	9	Angle of attack
367-80	-3	75	12	Stall	90	5	Proximity to V_{min}	1.20	15	7	Airspeed

[a]Estimated

[b]Uncorrected angle of attack, corrected angle of attack roughly 2/3 uncorrected angle of attack

TABLE III.- MECHANICAL CHARACTERISTICS OF CONTROL SYSTEM

(a) Longitudinal control

Aircraft	VZ-3RY	CV-48	UF-XS	C-8A	BR 941		YC-134A	NC-130B		367-80
					1963	1966		A/C	Sim.	
Maximum stick or wheel deflection, in. aft in. forward	7 7	7.9 4.1	8.2 4	7.8 4.7	6 4.5	5-6 4.5	9 5	9.5 7	9.5 7	10.2 5.0
Maximum elevator deflection, deg up deg down	20 10	--- (stabilator)	40+BLC 22	25 15	35 25	30 24	30 20	50+BLC 35		24 14
Breakout force, including friction, lb			6		2	3	15	6	1	6
Average static friction,[a] lb			5		10	5	30	6	1	6
Force at full deflection, lb pull lb push			25 20		40 30	38 34	35 20	70 50	70 50	50 24
Average gradient, lb/in.			2-1/2		4	5	1	7-1/2	7-1/2	3-1/2
Pilot rating or comments			3		Longitudinal control satisfactory. Throttle friction too high due to detent.		Objectionable high friction high inertia	Undesirable	Acceptable	
Throttle deflection, in.					14	14				

[a]Defined as difference in force between increasing and decreasing deflection measured at a slow rate of movement.

TABLE III.- MECHANICAL CHARACTERISTICS OF CONTROL SYSTEM - Continued

(b) Lateral control

Aircraft	VZ-3RY	CV-48	UF-XS	C-8A	BR 941		YC-134A	NC-130B		367-80		
					1963	1966		A/C	Sim.	90 K	115 K	115 K
Stick or wheel	Stick	Stick	Wheel	Wheel	Stick	Stick	Wheel	Wheel	Wheel	Wheel	Wheel	Wheel
Maximum wheel deflection, deg	---	---	±105	+80	---	---	±120	±90	±90	±75	±75	±75
Maximum stick deflection, in. (or linear movement of wheel at rim, in.)	±7-1/2	±4	±14[a]	+9[b]	±4.5	±4.5	±16[a]	±11.7[a]	±11.7[a]	±8.3[b]	±8.3[b]	±8.3[b]
Maximum aileron deflection from neutral control, deg up deg down	--- ---		25 BLC 18 BLC	23 18	8 5	0 0	30 20	60 BLC 30 BLC		17 17	17 17	17 17
Maximum spoiler deflection, deg	50	arc type	57	48	44	34	80	None		48	48	48
Maximum differential propeller pitch, deg	±1.5	---	---	---	±5.4	±13.4	---	---	---	---	---	---
Breakout force including friction, lb			6	3	2	3	15	8	3	6	4	4
Average static friction,[c] lb			10	6	4	3	30	15	1.3	2	2	2
Force at full deflection, lb			18	14	15	18	30	25	22	17	15	60
Average gradient, lb/in.			1	1	3	4	1	1	1.6	1.3	1.5	5.5
Pilot rating or comments	Deflection too large, hits knee	Deficient due to high mass and inertia	3-1/2 Wheel throw too large, desire 60°		Satis-factory	Satis-factory but lag in pro-peller pitch	Objectionable high inertia	6-1/2	Accept-able	Satisfac-tory	3-1/2	4-1/2

[a]Wheel diameter = 15 in.

[b]Wheel diameter = 13 in.

[c]Defined as difference in force between increasing and decreasing deflection measured at a slow rate of movement.

TABLE III.- MECHANICAL CHARACTERISTICS OF CONTROL SYSTEM - Concluded

(c) Directional control

Aircraft	VZ-3RY	CV-48	UF-XS	C-8A	BR 941		YC-134A	NC-130B		367-80
					1963	1966		A/C	Sim.	
Maximum pedal deflection, in.		±3.25	±2.5	±3.6	±2.7	±2.8	±4.25	±3.75	±3.75	±2.5
Maximum rudder deflection, deg	25	25	36 right 44 left + BLC	50	40	40	27	60+BLC	---	25
Maximum differential propeller pitch, deg	±3	---	---	---	±2	±8	---	---	---	
Breakout force including friction, lb			3		10	10	22			
Average static friction,[a] lb			5		3	3		Dominated by dynamics	7	
Force at full deflection, lb			35		85	95		125	60	
Average gradient, lb/in.			20 (nonlinear)		30	34	3	30	16	
Pilot rating or comments			4 Rudder force gradient too low; desire 50 percent more		Satisfactory		Objectionable	6-1/2 Bad hysteresis	Acceptable	

[a]Defined as difference in force between increasing and decreasing deflection measured at a slow rate of movement.

TABLE IV.- CONTROL RESPONSE CHARACTERISTICS

(a) Longitudinal

	Aircraft	VZ-3RY	CV-48	UF-XS	C-8A	BR 941		YC-134A	NC-130B		367-80	
						1963	1966					
	Airspeed, k	60	55-60	55	70	60	60	70	70	80	85-90	115
Control power	$\ddot{\theta}_0$max, rad/sec^2	2.0	1.4 -1.0	0.55 -0.21		1.05 -0.75	0.50 -0.40	0.4	0.65 -0.45	1.05 -0.75	0.24 -0.20	0.43 -0.36
	$2\xi\omega$, 1/sec	3	0.8	1.1		1.4	1.0	1.4	1.9	1.9		
	Nose up $\Delta\theta$ in 1 sec,[a] deg		18 / 14[b]	6.7		11.8	6.6	4.5	8.0	12.9		
	$t_{\Delta\theta=10°}$,[a] sec		0.8	1.2		0.9	1.2	1.5	1.2	1.0		
	Pilot rating	3	3	3 nose up 3-1/2 nose down		3-1/2	3-1/2	4-1/2	4	3-1/2	3-1/2	
Sensitivity	$\ddot{\theta}_0$/in., rad/sec^2/in.		0.20	0.06		0.17	0.10	0.06	0.07	0.11	0.03	
	Pilot rating										3-1/2	

[a]Computed for single degree of freedom with 0.1-sec transport lag and 0.3 sec control ramp.
[b]Measured.

TABLE IV.- CONTROL CHARACTERISTICS - Continued

(b) Lateral

	Aircraft	VZ-3RY	CV-48	UF-XS	C-8A		BR 941		YC-134A		NC-130B		367-80	
					With spoilers	Without spoilers	1963	1966	With spoilers	Without spoilers				
	Airspeed, k	60	55-60	55	70	70	60	60	80	80	70	85	85-90	115
Control power	$\ddot{\phi}_0$max, rad/sec^2	1.35	0.7	0.50	0.6[a]	0.3	0.42	0.48	0.86[a]	0.50	0.32	0.43	0.55	0.32
	τ, sec	<1	3.3	1.3	0.8	0.8	1	~1.5	0.7	0.7	0.9	0.8	1.0	0.36
	ϕ_1, deg Meas.[b] Comp.[c]	17	10 10.5	7.0	6 6.8	3.4	6 5.4	4 6.8	9.6	5.6	4.1	5.0	7.0	4 2.9
	t_{30}, sec Meas.[b] Comp.[c]		1.6	2.1	2.1 2.2	3.4	2.4 2.4	2.2 2.1	1.8	2.4	3.0	2.6	2.0	4.2
	Pilot rating or comments	4	3-1/2- control power 3-1/2 to 4 damp	3	5	7	3	4 - due to control lag	3-1/2 undesirable nonlinearity	5	5	4	3	2
Sensitivity	$\ddot{\phi}_0$/in., rad/sec^2/in.	0.18	0.18	0.04	0.05[a]	0.03	0.14[a]	0.17[a]	0.03[a]	0.03	0.03	0.04	0.06	
	Pilot rating or comments						3		Low sensitivity					

[a]Nonlinear with deflection, sensitivity measured at 0 to 1-in. control deflection.

[b]Measured from initiation of pilot force.

[c]Computed assuming 0.1-sec transport lag plus 0.3-sec ramp input and single degree of freedom.

TABLE IV.- CONTROL RESPONSE CHARACTERISTICS - Concluded

(c) Directional

Aircraft		VZ-3RY	CV-48	UF-XS		C-8A	BR 941		YC-134A	NC-130 (unaugmented)		367-80 (unaugmented)	
							1963	1966					
Airspeed, k		60	55-60	55		70	60	60	70	70	85	85-90	115
Control power	$\ddot{\psi}_0$max, rad/sec^2	<0.3	0.33	Left 0.07	Right 0.27	0.32	0.18			0.21	0.32	0.09	0.12
	$2\xi\omega_d$, 1/sec		0.67	0.5	0.5	0.34	0.15			0.12	0.15	-0.16	-0.16
	$\Delta\psi$ in 1 sec,[a] deg		4.6 7[b]	1.0	3.9		3.0			3.3	5.1	1.5	2.0
	$t_{\Delta\psi=15°}$,[a] sec		1.7	3.9	1.8		2.0			1.9	1.5	2.7	2.4
	Pilot rating	8	3	5	3		3			4	3-1/2	3	2-1/2
Sensitivity	$\ddot{\psi}_0$/in., rad/sec^2/in.		0.10	0.07	0.07	0.16	0.06			0.06	0.09		
	Pilot rating, comment		3									Sensitivity a little high	
Maximum steady sideslip angle, β, deg			16[c]	22[d]	16		25		12[e]	18[f]		18	

[a] Computed for single degree of freedom with 0.1-sec transport lag plus 0.3-sec control ramp.

[b] Measured.

[c] "Desire a little more."

[d] True β believed to be 2/3 indicated value.

[e] Unsatisfactory lightening at $\beta > 10°$.

[f] Much higher β could have been developed, but there was concern about stalling fin.

TABLE V.- LATERAL-DIRECTIONAL CHARACTERISTICS

Aircraft	VZ-3RY	CV-48	UF-XS	C-8A	BR 941		YC-134A	NC-130 (unaugmented)	367-80 (unaugmented)	
					1963	1966				
Airspeed, k	60	55-60	55	70	60	60	80	70	85-90	115
ω_d, rad/sec	1.1	1.1	1.0	1.0	0.7		1.2	0.5	0.8	
ξ		0.3	0.25	0.17	0.1		0.14	0.12	-0.1	
$\xi\omega_d$, rad/sec		0.33	0.25	0.17	0.07		0.16	0.06	-0.08	
Period, sec		5	6.5	6	8.5		5.4	12.0	8.6	
PR for directional damping	6-1/2	3	3-1/2	3-1/2	4		4-1/2	6-1/2		
$\Delta\beta/\Delta\phi$	0.5			0.45	0.4			0.8	0.75	
PR for cross coupling	5			4-1/2(IFR)	4(IFR)			7-8(IFR)	7-8(IFR)	
L_β, 1/sec^2	-2.1	-1.2	-0.03		-0.32			-0.11	-1.05	
N_β, 1/sec^2	1.1	1.2	0.8		0.54			0.23	0.42	
$N_{\delta_L}/L_{\delta_L}$	0.16	0.25	-0.06		-0.01			-0.2	0.1	
τ_R, sec	1.1	3.3	1.3	0.8	1.0		0.7	0.9	1.0	
PR for roll damping	4	4	3	3	3				4	
Spiral $T_{1/2}$, sec						10				
Spiral T_2, sec			4	10			4		12.2	
PR for spiral stability			4-1/2			3	Unsatisfactory			

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